Hydrogeology and Ground-Water/ Surface-Water Relations in the Bajura Area of the Municipio of Cabo Rojo, Southwestern Puerto Rico

By JESÚS RODRÍGUEZ-MARTÍNEZ

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

Caribbean District Chief
U.S. Geological Survey
Water Resources Division
GSA Center
651 Federal Drive, Suite 400-15
Guaynabo, Puerto Rico 00965

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.0630	liter per second
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons (Mgal)	0.04381	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per day
square mile (mi^2)	259.0	hectare

Temperature: Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8 \times °C + 32$$

Transmissivity: the standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form of this unit, foot squared per day (ft^2/d), is used for convenience.

Abbreviated water-quality units used in this report:

mg/L milligram per liter
µS/cm microsiemen per centimeter at 25 degrees Celsius
µg/L microgram per liter

Acronyms used in this report:

NOAA National Oceanic and Atmospheric Administration
PRASA Puerto Rico Aqueduct and Sewer Authority
USGS U.S. Geological Survey

Hydrogeology and Ground-Water/Surface-Water Relations in the Bajura Area of the Municipio of Cabo Rojo, Southwestern Puerto Rico

By Jesús Rodríguez-Martínez

Abstract

A study of the hydrogeology and ground-water/surface-water relations in the Bajura area of the municipio of Cabo Rojo, southwestern Puerto Rico was conducted from October 1991 through September 1994. The study included an area of about 11 square miles in the municipio of Cabo Rojo.

The geology of the area is dominated by a series of volcanic and metamorphic rocks of upper Cretaceous and Jurassic age and by the Cotuí Limestone of Cretaceous age interbedded with gravels and sands. These rocks are overlain by surficial deposits of Quaternary and Tertiary age. The Ciénaga de Cuevas wetland appears to be a tectonic basin that formed as a result of localized block faulting.

The primary source of ground water is the water-table aquifer, a heterogeneous aquifer composed mostly of limestone and secondary amounts of gravels, sands, and clayey sands. The ground-water type in the study area is mostly calcium bicarbonate and marginally sodium bicarbonate. In general, the water meets the drinking-water standards of the U.S. Environmental Protection Agency.

Transmissivities in the study area range from 270 to 5,600 feet squared per day and the horizontal hydraulic conductivities range from 10 to 200 feet per day, based on well-performance data and slug tests. A storage coefficient of about 0.07 was estimated for the water-table aquifer in the Bajura area.

Ciénaga de Cuevas, a surface-water feature in Barrio Bajura, can be classified as a riverine intermittent wetland. This wetland ponds at least twice a year as a consequence of the two wet seasons that normally occur during April through May and from August through November; the August through November ponding is normally longer and more areally extensive. Surface water in the study area is predominantly of the calcium magnesium bicarbonate type and is suitable for most industrial, domestic, and agricultural uses. Water quality of the wetland appears to be greatly influenced by evaporation.

Recharge during the two wet seasons of 1993 was estimated to be about 777 million gallons for that part of the aquifer within the cone of depression of a Puerto Rico Aqueduct and Sewer Authority well field. This recharge comes from the overlying Ciénaga de Cuevas and a series of streams that drain the wetland. This recharge supplied as much as 85 percent of the 2.5 million gallons per day being pumped from the water-table aquifer. Piezometric data and the results of seepage runs conducted in the lower reach of Río Guanajibo during low-flow conditions in 1992 and 1993 indicated that no interaction was occurring between it and the aquifer.

The main landforms in the study area are the Ciénaga—a riverine intermittent wetland located in a topographic low—and the Cordillera Sabana Alta, Cerro Conde Avila, and Monte Grande highlands. The lower reach of the Río Viejo, as well as the Quebrada Pileta and Quebrada Mendoza, drains Ciénaga de Cuevas, and acts as drainage for the aquifer. The isotopic data supported the ground-water/surface-water relations determined from the piezometric data. Prior to development of the aquifer, the Ciénaga de Cuevas was most likely discharging to the underlying aquifer.

INTRODUCTION

The municipio of Cabo Rojo in southwestern Puerto Rico has undergone a significant increase in population from 34,045 in 1980 to 38,521 in 1990 (U.S. Department of Commerce, 1980, 1990). The increase in population in combination with the influx of visitors due to tourism has led to temporary shortages in the potable public water supply. The main source of water in this area is provided by the Puerto Rico Aqueduct and Sewer Authority (PRASA) from a well field in the Bajura area adjacent to the urban area of Cabo Rojo. This well field provides about 2.5 Mgal/d of water from the water-table aquifer in the Bajura area (Gómez-Gómez and others, 1984; Colón-Dieppa and Quiñones-Márquez, 1985; Torres-Sierra and Avilés, 1986). The pumpage in this well field will likely increase as the water demand in the Cabo Rojo area also increases. A wetland known as Ciénaga de Cuevas (hereafter referred to as the Ciénaga) overlies the aquifer in the Bajura area. The relation of the Ciénaga with the underlying aquifer and the occurrence and movement of ground water in the Bajura area were unknown prior to the completion of the present investigation.

Purpose and Scope

This report summarizes the results of a 3-year investigation conducted by the U.S. Geological Survey (USGS), in cooperation with the PRASA from October 1991 through September 1994 to define the hydrogeology and the ground-water/surface-water relations in the Bajura area of the municipio of Cabo Rojo (fig. 1). The objectives of this study were to define the hydrogeologic framework, the occurrence and movement of ground water, and the ground-water/surface-water relations of the Bajura area. Results of the study will assist the PRASA to optimize development of the aquifer in the Bajura area, while preserving or enhancing the hydrologic and ecologic values of the Ciénaga.

Approach

The objectives of the investigation were met by (1) constructing 14 piezometers (fig. 2; table 1) of which 12 were instrumented with continuous water-level recorders to determine the areal and seasonal change in hydraulic head, (2) measuring monthly water levels in wells already existing in the study area, (3) constructing two nests of stratified piezometers of three wells drilled to different depths to define vertical hydraulic gradient and hydraulic conductivity, (4) performing specific capacity and slug tests to determine the transmissive properties of the aquifer in the Bajura area, (5) conducting two seepage runs in the lower reach of the Río Guanajibo to determine the flow between it, the aquifer, and the Ciénaga, and (6) reviewing drillers' logs at existing wells and using these records in conjunction with lithologic data obtained during installation of piezometers to define the subsurface geology in the study area. In addition, a water-level stage recorder and a weather station, which both included a precipitation gage and pan-evaporation station, were installed in the Ciénaga. The locations of all piezometers, wells, and data-collection stations used in this study are shown in figure 2. Ground-water and surface-water samples were collected at selected sites in the study area to determine the concentration of major ions, nutrients, and deuterium and oxygen-18 composition (fig. 3).

Acknowledgments

The author is grateful to Mr. Pablo McDougall, Mr. Juan Ruíz, and Mr. Carlos Aymat for providing access to their properties, allowing the drilling of test wells, and the installing of data-collection equipment.

DESCRIPTION OF STUDY AREA

The Bajura study area encompasses about 11 mi^2 and includes the Ciénaga and its drainage basin, the lower reach of the Río Guanajibo, and part of the lower Río Guanajibo alluvial valley (fig. 1). The Bajura area consists of a semi-enclosed basin bordered by the Cordillera Sabana Alta to the northwest, the Cerro Conde Avila to the west, and the Monte Grande to the south. The Bajura area is bounded to the northeast and east by the Ciénaga and the lower reach of the Río Guanajibo alluvial valley (fig. 1). Land in the study area is used mostly for pasture or is left fallow.

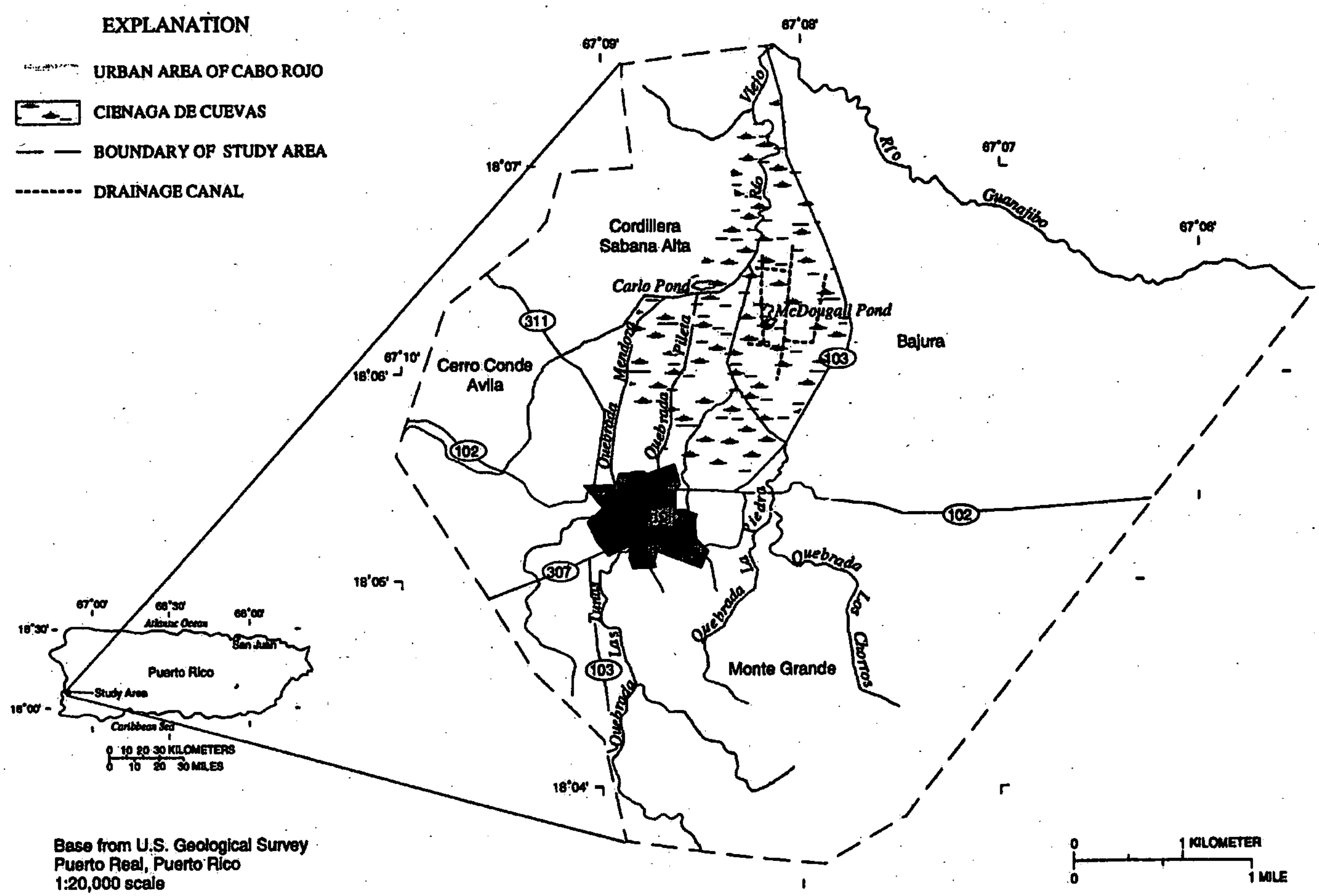


Figure 1. Location and extent of the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

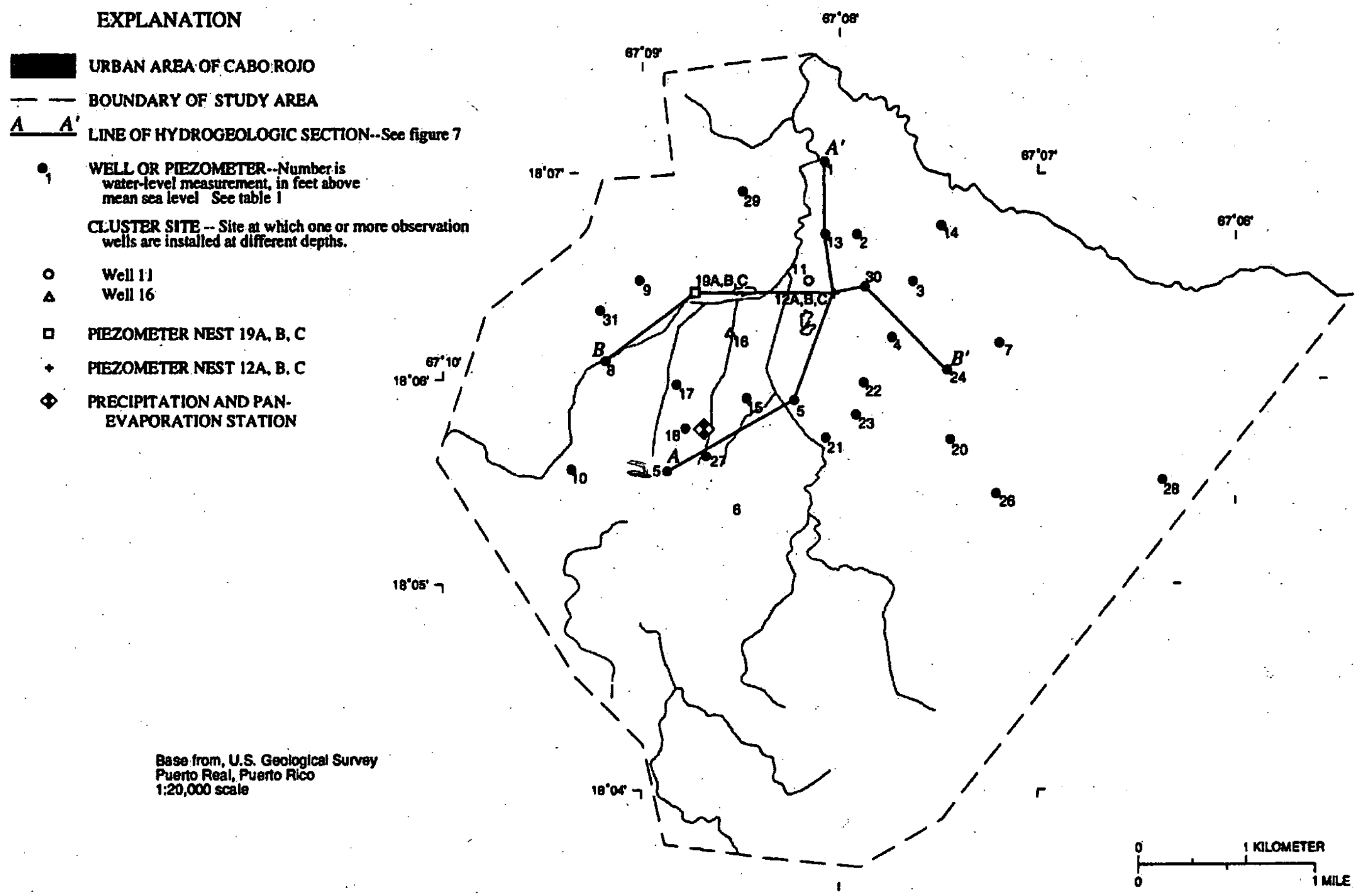


Figure 2. Location of test wells and pumping wells, lines of geologic sections, and meteorological station used in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

Table 1. Names, identification numbers, and locations of wells or piezometers used in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico

[Locations of well or piezometer are shown in figure 2. Site identification No.: Unique number for each site based on the latitude and longitude of the site. First six digits are latitude, next six digits are longitude. Latitude and longitude are given in degrees, minutes, and seconds. Use: DO, domestic supply well; OW, piezometer; PWS, public supply well. Depths are shown in feet below land surface. --, data not available]

Well or piezometer No.	Name	Site identification No.	Use	Depth of well	Open or screened depth interval in well	
1	PRASA 1	180705670804	PWS	190	85-135	abandoned
2	PRASA 2	180642670753	PWS	200	70-120	abandoned
3	Camarones	180626670738	DO	--	--	inactive
4	Fillipi	180616670744	DO	--	--	abandoned
5	PRASA 5A	180559670804	PWS	200	20-200	
6	López	180552670805	PWS	--	--	inactive
7	Ubaldino	180620670709	DO	--	--	I
8	PRASA Radio	180605691002	PWS	440	55-440	
9	Polígono	180641670906	DO	--	--	
10	PRASA Beldford	180545670922	PWS	--	--	
11	Cr-tw1	180627670806	OW	24	5-15	
12A	Cr-tw2A	180628670758	OW	15	10-15	
12B	Cr-tw2B	180628670758	OW	67	60-65	
12C	Cr-tw2C	180628670758	OW	114	108-113	
13	Cr-tw3	180643670804	OW	30	20-30	
14	Cr-tw4	180650670737	OW	25	15-25	
15	Cr-tw5	180558670833	OW	25	15-25	
16	Cr-tw6	180617670833	OW	30	20-30	
17	Cr-tw7	180604670851	OW	40	30-40	
18	Cr-tw8	180547670848	OW	35	25-35	
19A	Cr-tw9A	180628670843	OW	24	19-24	
19B	Cr-tw9B	180628670843	OW	79	74-79	
19C	Cr-tw9C	180628670843	OW	109	104-109	
20	Cr-tw10	180547670731	OW	42	31-41	
21	PRASA Club de Leones	180550670802	PWS	150	90-150	
22	PRASA Bajura 2	180557670755	PWS	--	--	
23	PRASA 3	180552670757	PWS	--	--	
24	PRASA 8	180609670732	PWS	200	60-200	
25	PRASA Ana María	180539670854	PWS	200	40-200	
26	Oscar	180529670716	DO	--	--	dug well
27	Garaje Municipal	180542670854	DO	--	--	DTOP
28	USGS-tw	180534670621	OW	85	--	
29	Pozo Toro	180706670823	DO	--	--	
30	PRASA McDougall	180626670751	PWS	175	50-175	
31	Aymat Dairy	180617691002	DO	--	--	

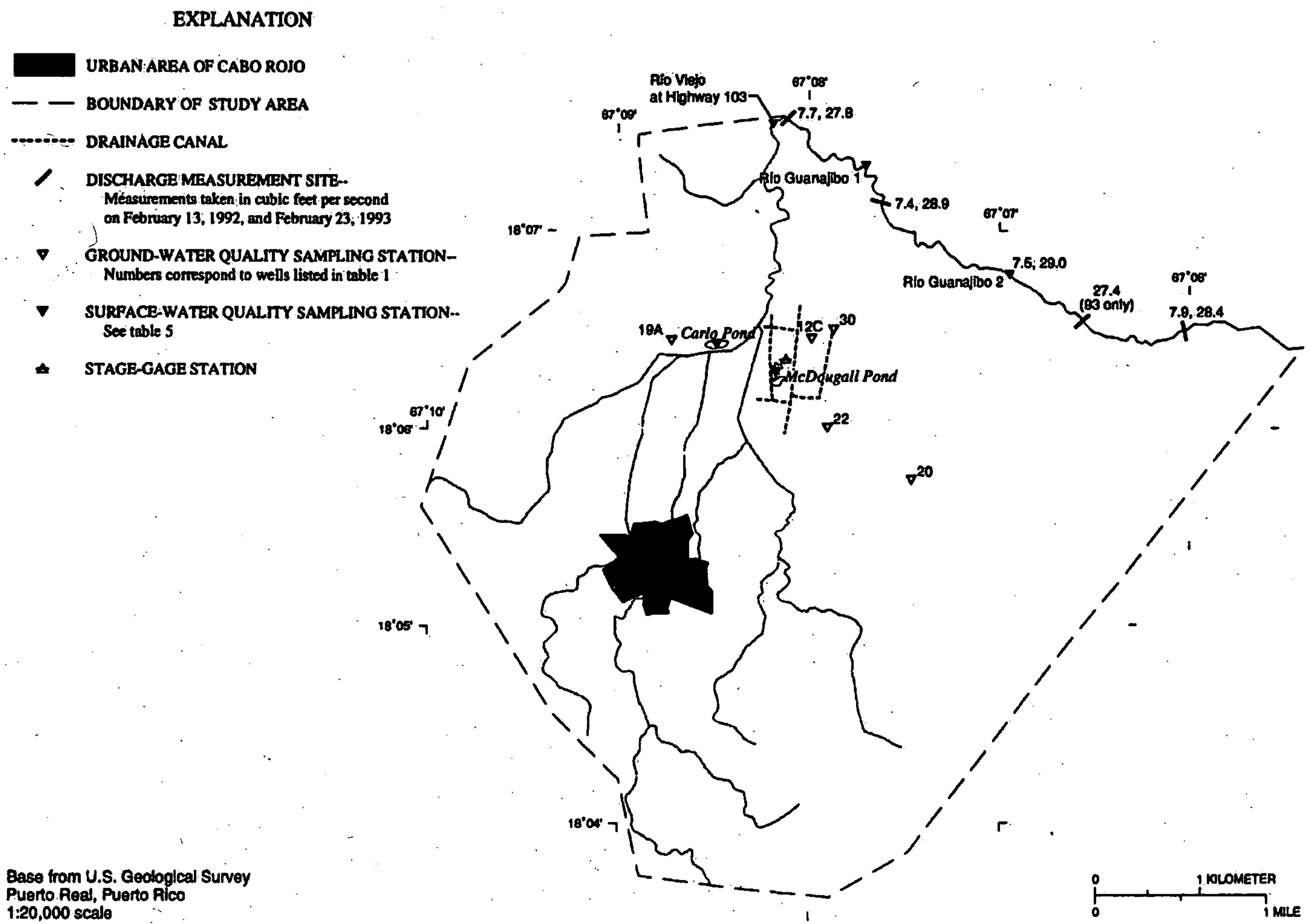


Figure 3. Location of discharge measurement sites and ground-water and surface-water quality sampling stations in the Bajura area, municipio of Cabo Rojo southwestern Puerto Rico.

Landforms and Drainage in the Study Area

The main landforms in the study area are the Ciénaga—a riverine intermittent wetland located in a topographic low—and the Cordillera Sabana Alta, Cerro Conde Avila, and Monte Grande highlands (fig. 1). The Ciénaga is in the western end of the lower reach of the Río Guanajibo alluvial valley. The highlands in the study area are drained by the Quebrada Mendoza, Quebrada Pileta, and Quebrada La Piedra; intermittent streams that flow north into the Río Viejo. The Río Viejo flows into the Río Guanajibo, which is the primary regional drainage feature. Drainage canals that flow into the Río Viejo were constructed during the 1930's. However, the effectiveness of these canals is currently limited due to sedimentation. The land-surface altitude in the low-lying part of the study area ranges from 26 ft above mean sea level in the Ciénaga to 40 ft above mean sea level near the Río Guanajibo. The maximum altitude of the highlands ranges from 204 ft above mean sea level in the Cordillera Sabana Alta to 295 ft above mean sea level in the Cerro Conde Avila.

Climate

The annual rainfall recorded during 1993 in the Bajura area was 57.1 in., slightly more than the average annual rainfall of 55.1 in. recorded by the National Oceanic and Atmospheric Administration (1960-70) in the municipio of Cabo Rojo from 1958 to 1968. Mean monthly rainfall during 1959-68 ranged from a minimum of 0.8 in. in February to a maximum of 8 in. in August (fig. 4). Monthly rainfall during 1993 ranged from 2 in. in July (driest month) to 9.9 in. in August (wettest month) and differed substantially from the mean monthly rainfall for some months (fig. 4). Analysis of historic and current rainfall data indicates the occurrence of two rainy seasons in the study area. The first rainy season normally occurs during April and May; the second, from August to November.

The nearest pan-evaporation station operated by the NOAA is at the Lajas Agricultural and Experimental Station, about 12 mi southeast of the study area. The mean annual pan evaporation for a 43-year period at the Agricultural Station was 69 in. During 1993, a pan evaporation of 57.5 in. was recorded at the meteorological station installed in the Bajura area (fig. 2). Analysis of the daily meteorological data indicates that pan evaporation exceeded precipitation during 279 days in 1993. The number of days per month that pan evaporation exceeded precipitation during 1993 ranged from 15 days in September to 28 days in December (fig. 5).

Geology

The geology of the Bajura area was described and mapped by Volckmann (1984). The geologic units exposed in the Bajura area range from Upper Jurassic to Quaternary in age. These are, from oldest to youngest, an unnamed serpentinite unit, the Yauco Formation, the Cotuí Limestone, the Sabana Grande

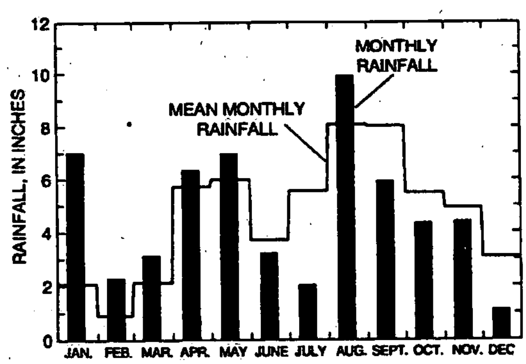


Figure 4. Monthly rainfall in the Bajura area during 1993 and mean monthly rainfall at the Cabo Rojo station, municipio of Cabo Rojo, southwestern Puerto Rico, 1958 through 1968.

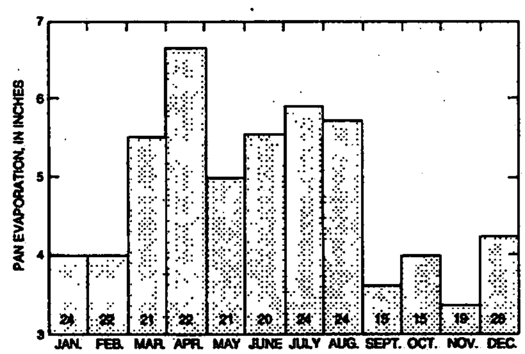


Figure 5. Monthly pan evaporation during 1993 and number of days pan evaporation exceeded rainfall each month in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

Formation, and the Lajas Formation (fig. 6). These units are overlain mostly by unnamed Tertiary quartz sand deposits and assorted Quatenary surficial deposits resulting from the coalescing of small alluvial fans and the episodic flooding of the nearby Río Guanajibo.

According to Volckmann (1984), the serpentinite unit of Upper Jurassic to Lower Cretaceous age is characterized by extreme brecciation and shearing that locally produces a strong foliation within the unit. The Yauco Formation of Upper Cretaceous age consists of interbedded calcareous siltstone, limestone, fine-grained tuff, and conglomerate. The Lajas Formation of Upper Cretaceous age consists of basalt flows and minor tuffs. The Cotuí Limestone of Upper Cretaceous age is a thickly bedded to massive, dense bioclastic limestone generally composed of mollusk fragments in an abundant coarse cement. The Upper Cretaceous Sabana Grande Formation consists of andesitic crystal-lithic tuff, tuff-breccia, and conglomerate with minor basaltic lava and breccia. The Tertiary quartz sand deposits are irregularly shaped and distributed and consist mainly of quartz grains and minor hematite or limonite and clay. The overlying surficial deposits are composed of clay, silt, sand, clayey sand, and local gravel deposits. The swamp deposits, rich in organic material, are limited to the Ciénaga de Cuevas.

The major structural features in the study area are a set of northeast-southwest trending high-angle faults which offset Upper Cretaceous rocks (Volckman, 1984). The Ciénaga de Cuevas area appears to be a graben, a tectonic basin that formed as the result of localized block faulting. Santos and Kauffman (1989) found evidence of structural deformation associated with the contact interval between the Cotuí Limestone and the Sabana Grande Formation in the form of half-graben blocks. The influx of volcanic material during the deposition of the Sabana Grande Formation locally inhibited the deposition of the Cotuí Limestone and, as a result, the Cotuí Limestone was deposited as a series of separated lenticular bodies in the Guanajibo alluvial valley. This contemporaneous volcanic activity and subsequent episode of block faulting appear to have segmented most of the Cotuí Limestone into smaller and separated lenticular bodies and structural blocks as observed in its outcrop pattern (field inspection; Volckmann, 1984).

The primary lithologies in the subsurface of the study area are shown in sections *A-A'* and *B-B'* (fig. 7). In the absence of test hole lithologic data, this information was obtained from drillers' logs of the PRASA wells and piezometers installed for this study. These data show that an upper layer of clay, rich in organic fine-grained matter at its top, overlies the Ciénaga area. This organic-rich clay, dark brown to grayish-black in color, ranges in thickness from 2 to 4 ft. This organic clay is usually underlain by a zone of silty and sandy clay that ranges from 5 to 35 ft thick. This silty and sandy clay unit is underlain by lenticular deposits of sand and gravel which in turn are underlain by a limestone unit that the author speculates is a subsurface equivalent of the Cotuí Limestone. The silty and sandy clay is locally underlain by the limestone unit.

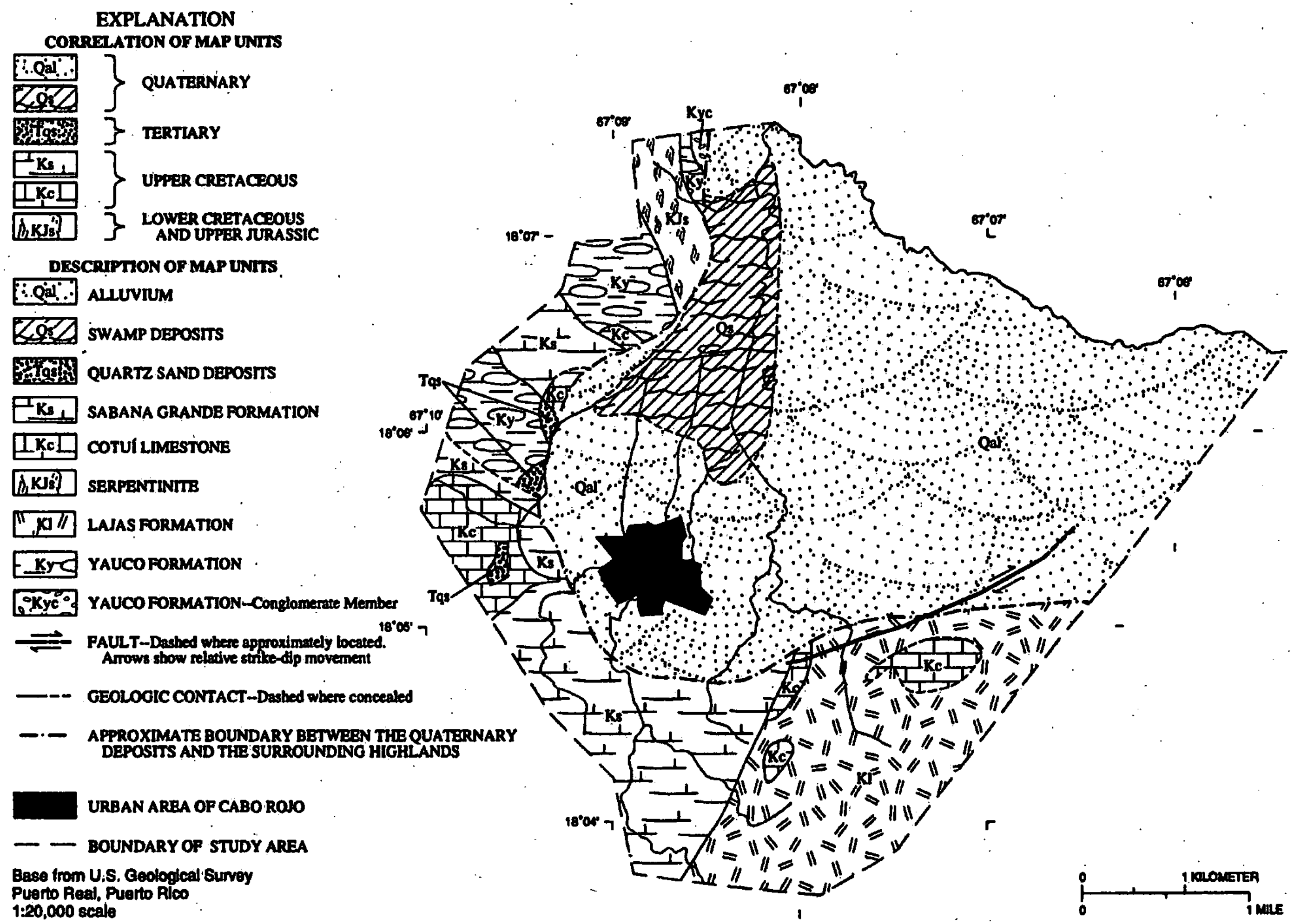


Figure 6. Major surficial units in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

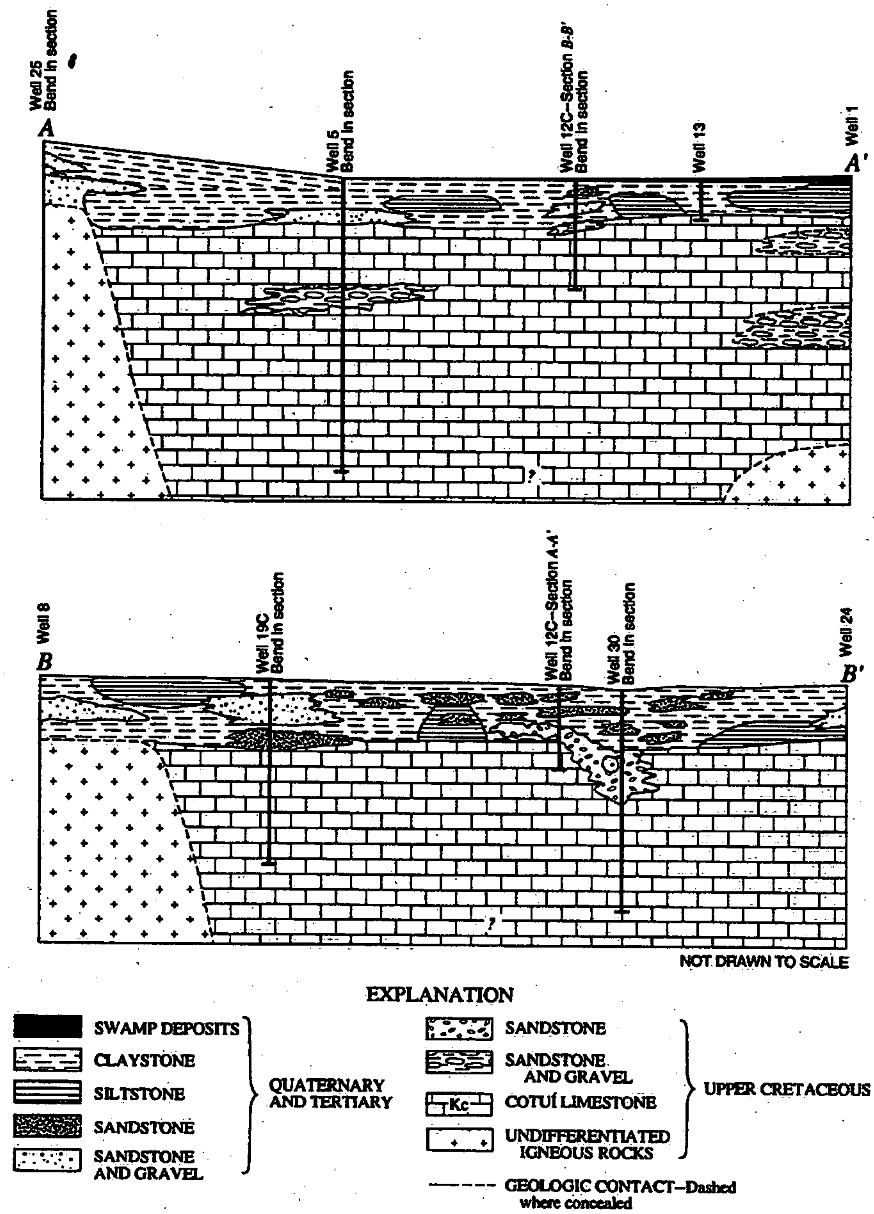


Figure 7. Generalized geologic sections *A-A'* and *B-B'* in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

GROUND-WATER HYDROLOGY

Ground water generally occurs under water-table conditions in the limestone, and alluvial deposits of clayey sand and gravel. Potentiometric maps prepared for April 29, June 30, July 23, and September 29, 1993, indicate the direction of ground-water movement is maintained towards a cone of depression produced by the public water-supply well field and by drainage to the lower reach of the Río Viejo, Quebrada Mendoza, and Quebrada Pileta.

Occurrence and Movement

Ground water occurs under water-table conditions in the limestone and overlying alluvial deposits of clayey sand and gravel. Generally, depth to water ranges from 4 to 38 ft below land surface in the study area. The maximum aquifer thickness is not known but serpentinite, believed to be the bottom of the aquifer, has been reported in drillers' logs at depths ranging from 125 to 250 ft for several deep wells in this area.

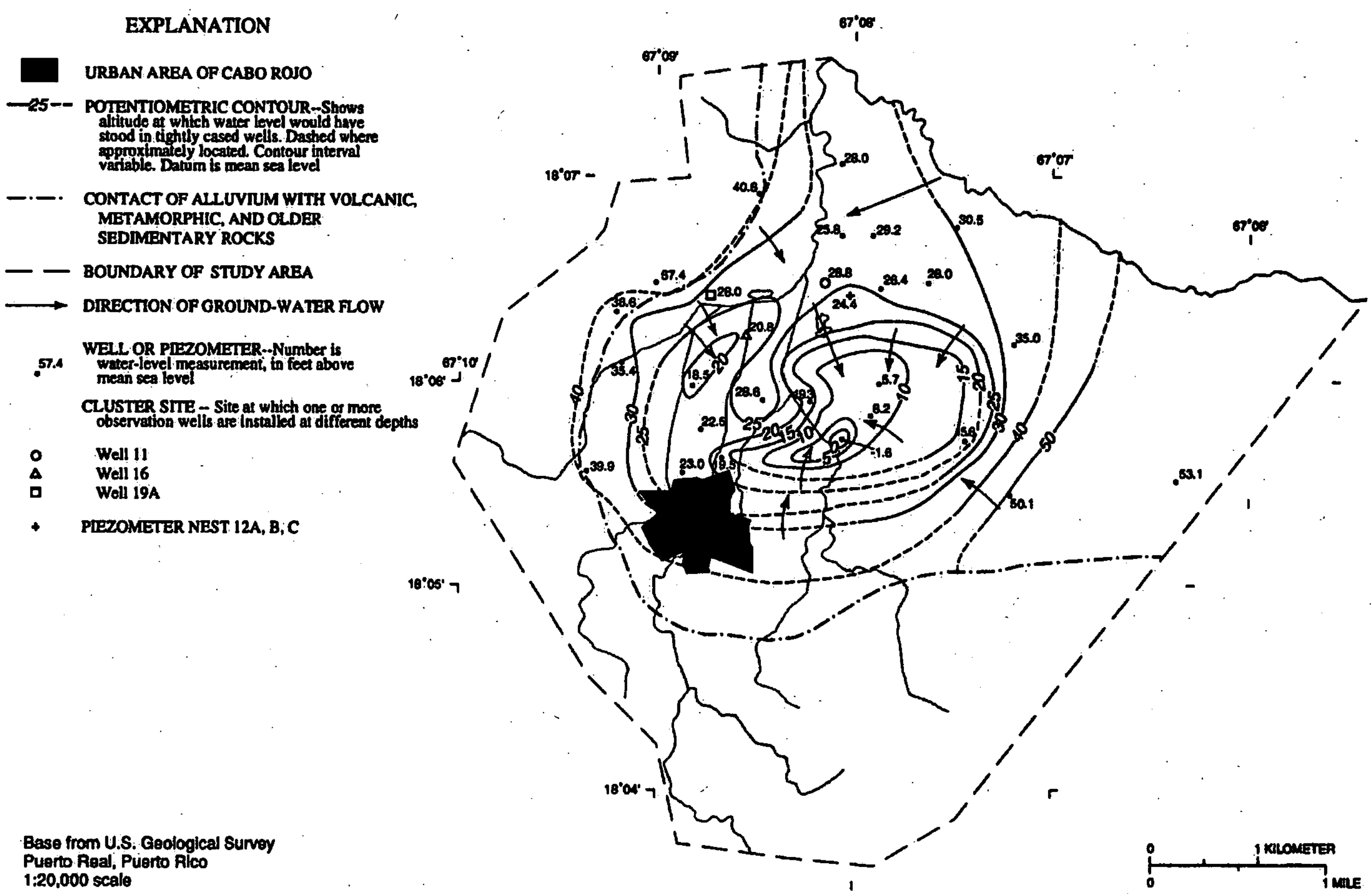
Ground-water-level data were collected for April 29, June 25, July 23, and September 29, 1993 (fig. 8). These dates were selected to define the areal change of the potentiometric surface across an annual cycle of wet season (April-May) to dry season (June-July) to wet season (August-November). The direction of ground-water movement remained relatively constant through the seasonal changes. Although flow patterns remained the same, the altitude of the water-table surface changed seasonally and by location. Seasonal head changes of 3, 6, and 4 ft occurred in wells 11, 16, and 19A (fig. 9). Ground-water flow is dominated by a cone of depression toward wells 21, 22, and 23 (refer to fig. 2 for well location), which form the principal water-supply well field in the Bajura area. Outside of the influence of this cone of depression, ground-water flow is toward the lower reach of the Río Viejo, Quebrada Mendoza, and Quebrada Pileta.

Vertical hydraulic gradients (fig. 10) in the study area are indicated by water-level data obtained from the two piezometer nests (sites 12 and 19). The head in the shallow piezometer was the highest in the two piezometer nests, whereas the head in the intermediate piezometer was equal or slightly higher than the head in the deep piezometer during all of 1993 (fig. 10). The shallow piezometers in both nests are completed in the clayey sand and claystone of the upper unit, whereas the intermediate and the deep piezometers are completed in the limestone and gravel facies. The difference in head between the shallow and the intermediate and deep piezometers could be the result of the vertical to lateral anisotropy in hydraulic conductivity caused by the finer grained materials composing the upper unit and the considerably more permeable nature of the limestone and gravel facies. The limestone and gravel facies thus act as internal drainages for the aquifer with the result that the head in these facies is lower than in the upper unit.

Hydraulic Characteristics

The most favorable hydraulic characteristics in the Bajura area for ground-water withdrawals coincide with those sites where the limestone is thickest. The alluvial sand and gravel beds present in the study area are lenticular and discontinuous. Consequently, their importance as water-bearing units appears to be secondary to that of the limestone. Data obtained during construction of the piezometers indicate that at most sites the sand and gravels deposits are in hydraulic connection with the limestone and, for the purpose of this report, the limestone and alluvial deposits can be considered as one heterogeneous aquifer.

Well-performance data and slug tests conducted on selected test wells drilled as part of this study were used to estimate the hydraulic characteristics of the aquifer in the Bajura area. Specific capacities in the Bajura area ranged from 2 to 18 (gal/min)/ft of drawdown (table 2). Similarly, transmissivities estimated from specific capacities ranged from 270 to 5,600 ft^2/d (table 2). The horizontal hydraulic conductivity estimates in the aquifer obtained from slug tests ranged from 10 to 200 ft/d (table 3) (Bouwer and Rice, 1976). The horizontal hydraulic conductivity not only changes areally but also with depth as demonstrated by the results of the slug tests conducted in piezometers 19B and 19C. The hydraulic conductivity estimated in piezometer 19B (intermediate piezometer open from 74 to 79 ft below land surface) was 200 ft/d, whereas the estimate for piezometer 19C (deep piezometer open from 104 to 109 ft below land surface) was 30 ft/d.



A. **April 29, 1993**

Figure 8. Configuration of the potentiometric surface and generalized directions of ground-water flow in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico, for *(A)* April 29, 1993, *(B)* June 30, 1993, *(C)* July 23, 1993, and *(D)* September 29, 1993.

EXPLANATION

URBAN AREA OF CABO ROJO

—25— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval variable. Datum is mean sea level

CONTACT OF ALLUVIUM WITH VOLCANIC, METAMORPHIC, AND OLDER SEDIMENTARY ROCKS

BOUNDARY OF STUDY AREA

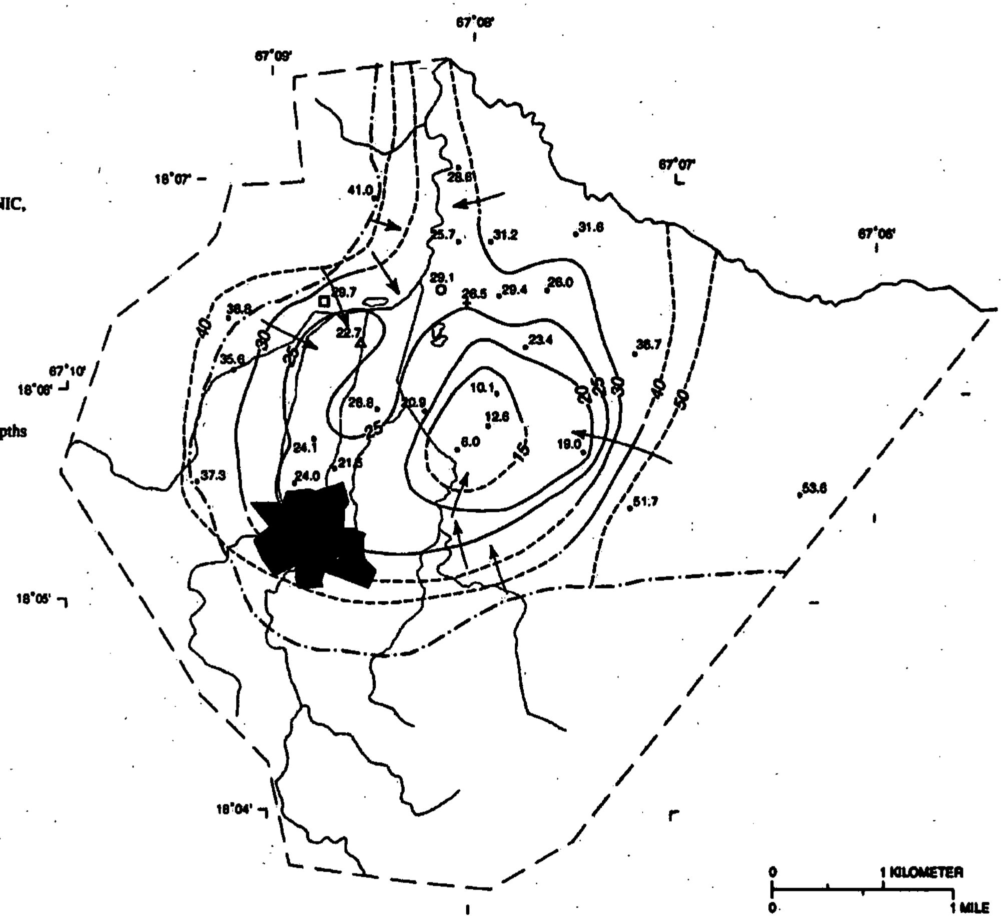
DIRECTION OF GROUND-WATER FLOW

36.8 WELL OR PIEZOMETER--Number is water-level measurement, in feet above mean sea level

CLUSTER SITE -- Site at which one or more observation wells are installed at different depths

- Well 11
- Well 16
- Well 19A

PIEZOMETER NEST 12A, B, C



Base from U.S. Geological Survey
Puerto Real, Puerto Rico
1:20,000 scale

***B.* June 30, 1993**

Figure 8.—*Continued.*

EXPLANATION

URBAN AREA OF CABO ROJO

—25— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval variable. Datum is mean sea level

—·—· CONTACT OF ALLUVIUM WITH VOLCANIC, METAMORPHIC, AND OLDER SEDIMENTARY ROCKS

— — BOUNDARY OF STUDY AREA

——► DIRECTION OF GROUND-WATER FLOW

•31.0 WELL OR PIEZOMETER--Number is water-level measurement, in feet above mean sea level

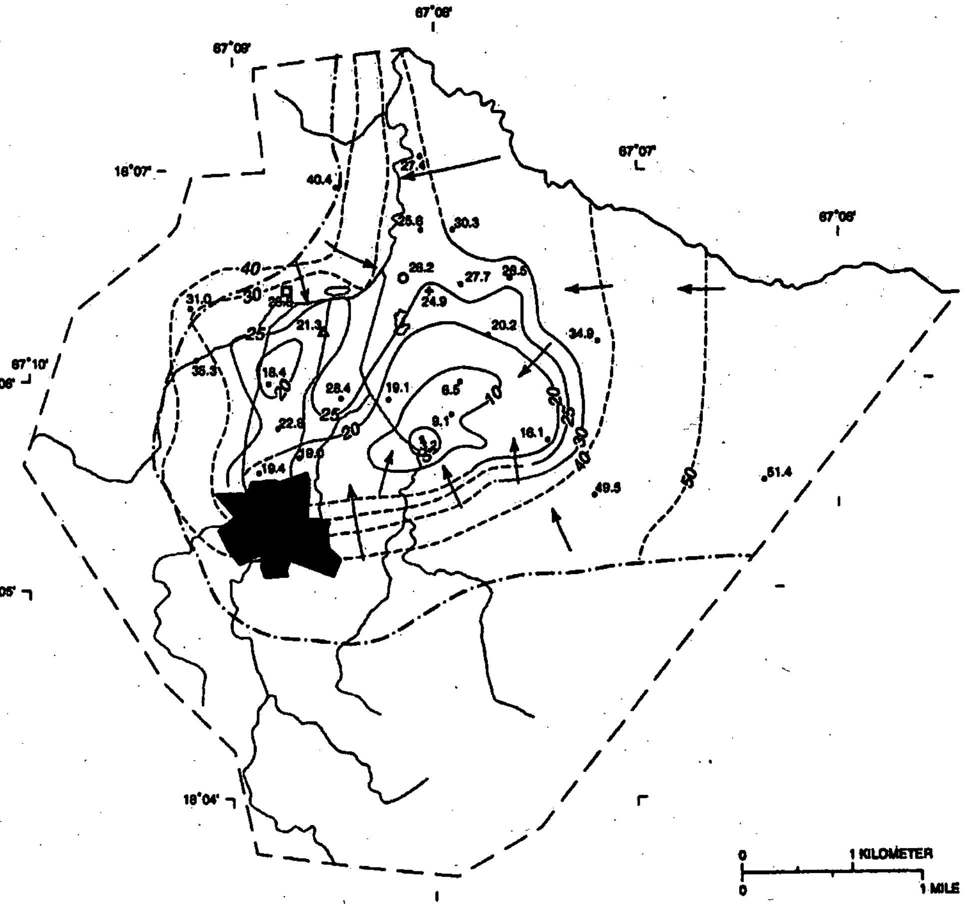
CLUSTER SITE--Site at which one or more observation wells are installed at different depths.

○ Well 11

△ Well 16

□ Well 19A

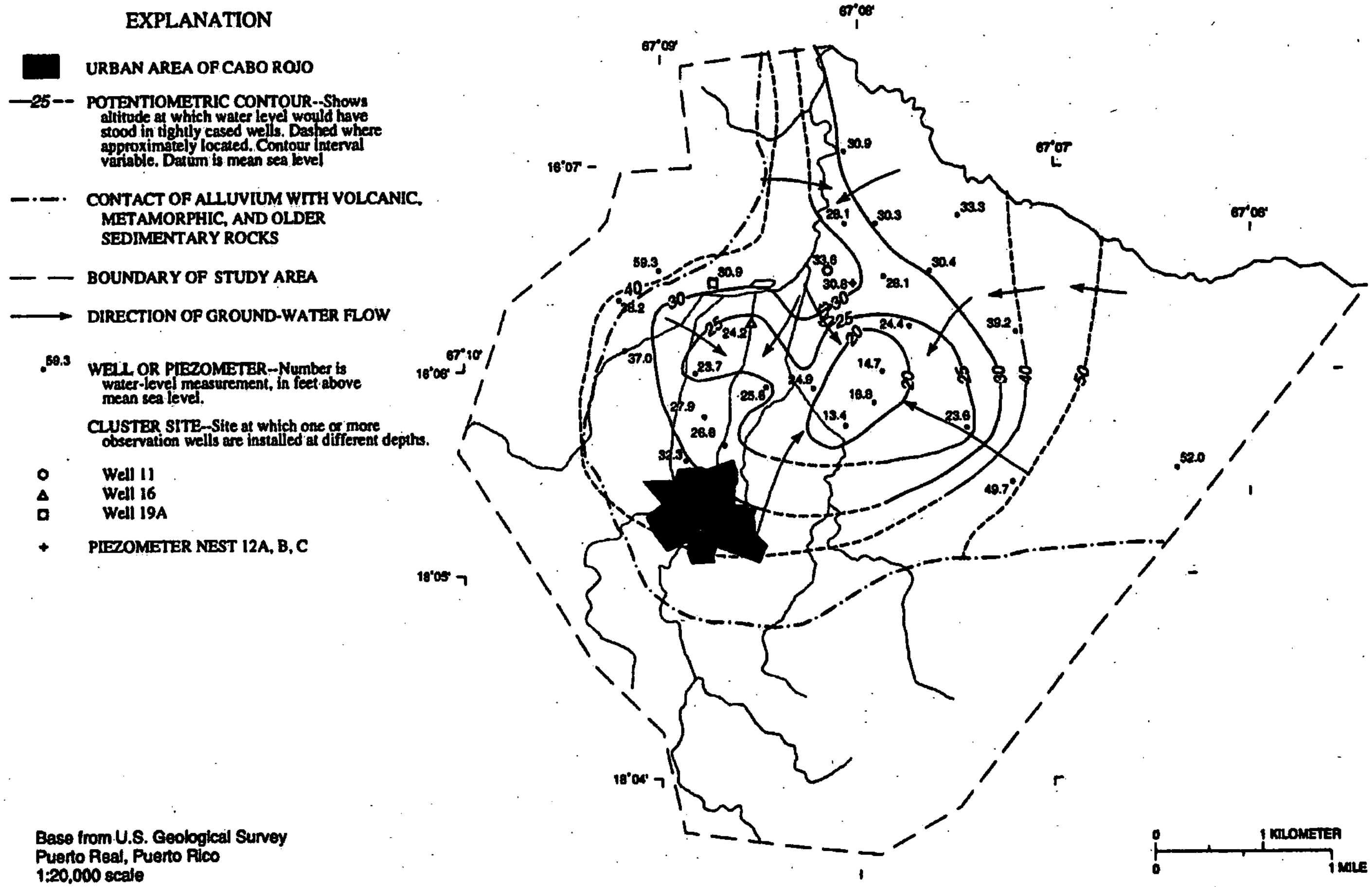
+ PIEZOMETER NEST 12A, B, C



Base from U.S. Geological Survey
Puerto Real, Puerto Rico
1:20,000 scale

***C.* July 23, 1993**

Figure 8.—*Continued.*



***D.* September 29, 1993**

Figure 8.—*Continued.*

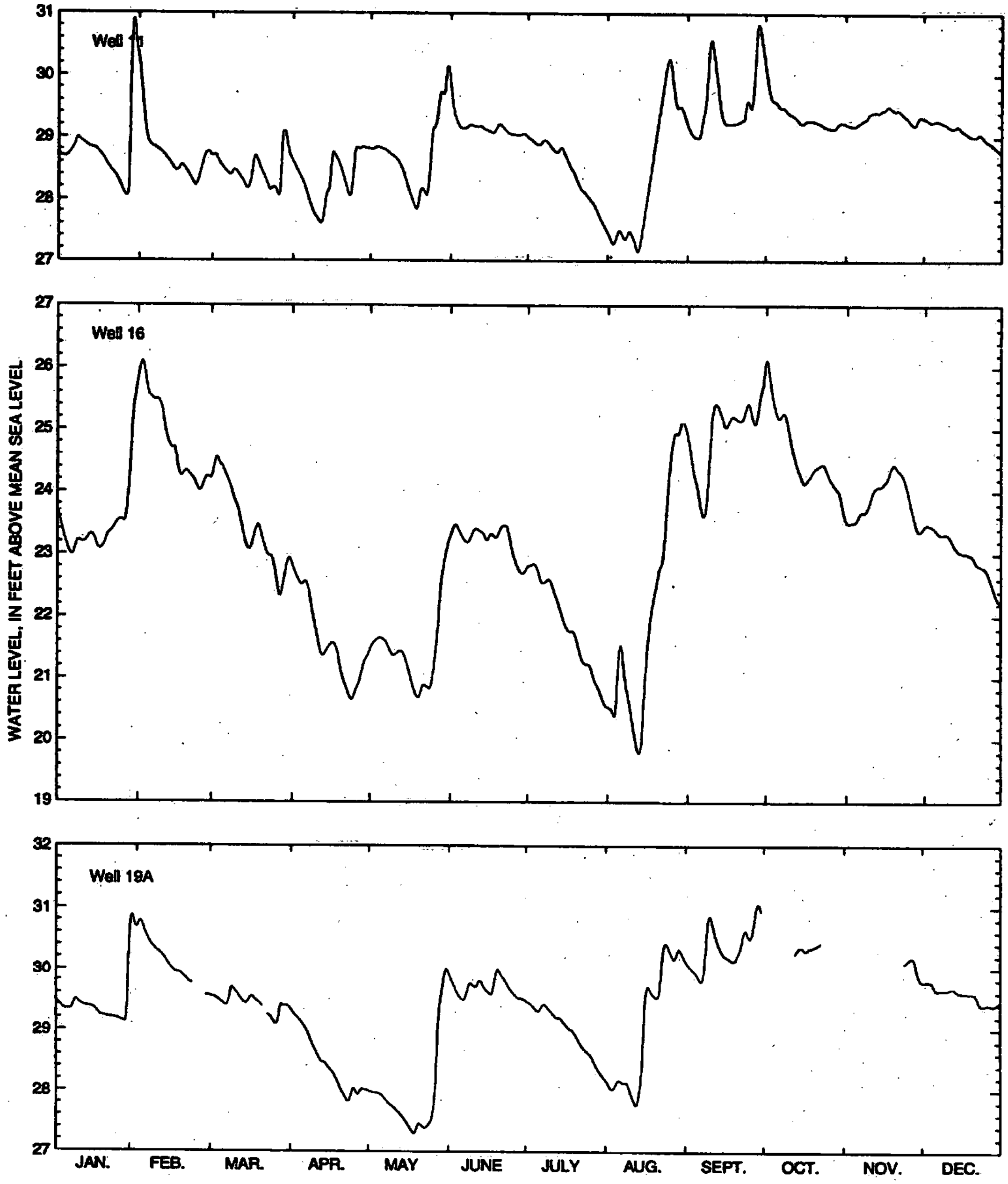


Figure 9. Daily mean ground-water levels in wells 11, 16, and 19A in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico, 1993.

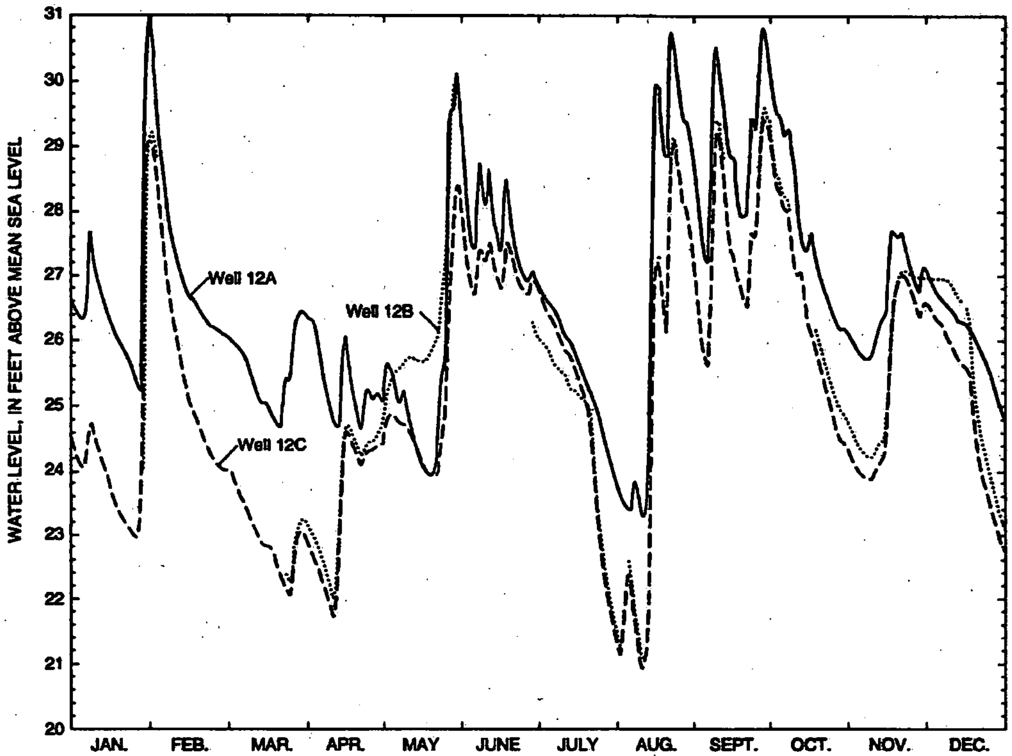


Figure 10. Daily mean ground-water levels at a selected piezometer nest in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico, 1993.

Table 2. Well-performance data and estimated aquifer transmissivity values in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico

[Depths are shown in feet below land surface. Transmissivity was estimated using methods described in Theis and others (1963). in., inch; (gal/min)/ft, gallon per minute per foot; ft²/d, foot squared per day; --, data not available]

Well or piezometer No. (fig. 2)	Well diameter (in.)	Open or screened depth interval in well	Length of test (hours)	Specific capacity [(gal/min)/ft of drawdown]	Transmissivity (ft²/d)
1	12	85-135	40	3	[1]670
5	12	20-200	48	18	5,600
8	16	55-400	48	1	[1]270
21	18	90-150	48	8	1,300
25	10	40-200	40	8	1,400
30	10	50-175	48	5	650

[1] Length of drawdown test not given in well schedule, but was estimated at 48 hours, which is a typical test period used by drillers in the study area.

Table 3. Hydraulic conductivities in the study area as determined from single-well slug tests in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico

[Depths are shown in feet below land surface. Horizontal hydraulic conductivities from Bouwer and Rice, 1976. ft/d, foot per day]

Well or piezometer No. (fig. 2)	Open or screened depth interval in well	Horizontal hydraulic conductivity (ft/d)
12A	10-15	50
13	20-30	10
19B	74-79	200
19C	104-109	30

This variation in hydraulic conductivity could be related to the heterogeneous distribution of fractures and enhanced solution along bedding planes and joints in limestone, or the presence of interbedded sand and gravel layers.

An indirect method was used to obtain the order of magnitude of the storage coefficient of the aquifer in the Bajura area. This method consisted of dividing the total pumpage from June 25 to July 23, 1993, by the reduction in aquifer storage (dewatering) in the cone of depression for the same period (fig. 11). The reduction in aquifer storage (fig. 11) was determined as follows: (a) the water-level change (decline) in the piezometers within the cone of depression was contoured; (b) the subareas defined by successive contours were determined assuming that the decline in water level was the average of the water-level declines in the wells within the two enclosing contours; and (c) the reduction in storage volume (dewatering) was obtained by multiplying the individual subareas by their respective average water-level declines and summing the resulting volumes of the vertically discrete intervals. Based on a withdrawal rate of 2.5 Mgal/d from the PRASA well field, a storage coefficient of 0.07 was computed; this value agrees fairly well with the 0.10 assumed in preliminary analyses for the type of deposits which constitute the aquifer. Estimates of the storage coefficient for the Bajura area in this manner are considered appropriate because after the high water conditions of June 25 to July 23, no ponding of water existed within the wetland, streamflow was nonexistent or minimal, rainfall was insignificant (about 2.3 in.) and, consequently, the effect of recharge was nonexistent or minimal.

The outcrop area of the Cotuí Limestone is mostly discontinuous and irregularly distributed as mentioned in the section on "Geology." From field inspection during this study and interpretation by Volckmann (1984), it can be deduced that a significant number of these separate lenticular and structural blocks of the Cotuí Limestone in the outcrop area are not continuous with the underlying facies where the aquifer is located. As a result of this discontinuity, the actual outcrop area of the Cotuí Limestone that is hydraulically connected to the aquifer is considerably less than the total outcrop area of this geologic unit. Delineation of the total outcrop area of the Cotuí Limestone that is hydraulically connected to the underlying aquifer was beyond the scope of this investigation and is not discussed further in this report.

Water Quality

In order to characterize the ground-water quality in the Bajura area, water samples were collected from four wells to be analyzed for common ions and nutrients (table 4). The prevalent ground-water type is mostly calcium bicarbonate and marginally sodium bicarbonate (fig. 12). The calcium bicarbonate water is present in the deep parts of the aquifer and is apparently associated with the limestone facies. The sodium bicarbonate water is associated with the shallower terrigenous facies. The large concentrations of sodium and potassium in the shallow ground water probably results from the dissolution of feldspar minerals present in the sand and gravel (mostly composed of volcanic clasts) and the subsequent release of these two ionic species into solution. This dissolution of the feldspar minerals results from the downward movement of recharging waters enriched with soil-derived carbon dioxide (CO_2).

The quality of ground water in the study area is within the recommended U.S. Environmental Protection Agency (1991) secondary drinking water standards. Dissolved-solids concentration was 651 mg/L in piezometer Cr-tw-9a (well 19A), which penetrated to a depth of 24 ft below land surface. This concentration exceeds the maximum level of 500 mg/L for public water supply recommended by the U.S. Environmental Protection Agency (1991).

EXPLANATION

URBAN AREA OF CABO ROJO

—1.5— LINE OF EQUAL WATER-LEVEL DECLINE—Dashed where approximately located. Interval is variable

—·— CONTACT OF ALLUVIUM WITH VOLCANIC, METAMORPHIC, AND OLDER SEDIMENTARY ROCKS

— — BOUNDARY OF STUDY AREA

• WELL OR PIEZOMETER

CLUSTER SITE—Site at which one or more observation wells are installed at different depths.

△ Well 16

□ Well 19A

+ PIEZOMETER NEST 12A, B, C

ESTIMATION OF COEFFICIENT OF STORAGE

A_3 = 15,061,760 feet^2

A_2 = 22,700,224 feet^2

$A_3 + A_2$ = 3.51 kilometer^2

$V_3 = A_3 \times 3.5$ feet = 52,716,160 feet^3

$V_2 = A_2 \times 2.5$ feet = 56,750,560 feet^3

Total downward volume = 109,446,720 feet^3 (June 25-July 23)

Total pumpage = 7,384,812 feet^3 at 1,972,800 gallons per day (281,828 feet^3 per day) (June 25-July 23)

Coefficient of storage =

$$(\gamma) = \frac{7{,}384{,}812 \text{ feet}^3}{109{,}466{,}720 \text{ feet}^3} = 0.0675 - 0.07$$

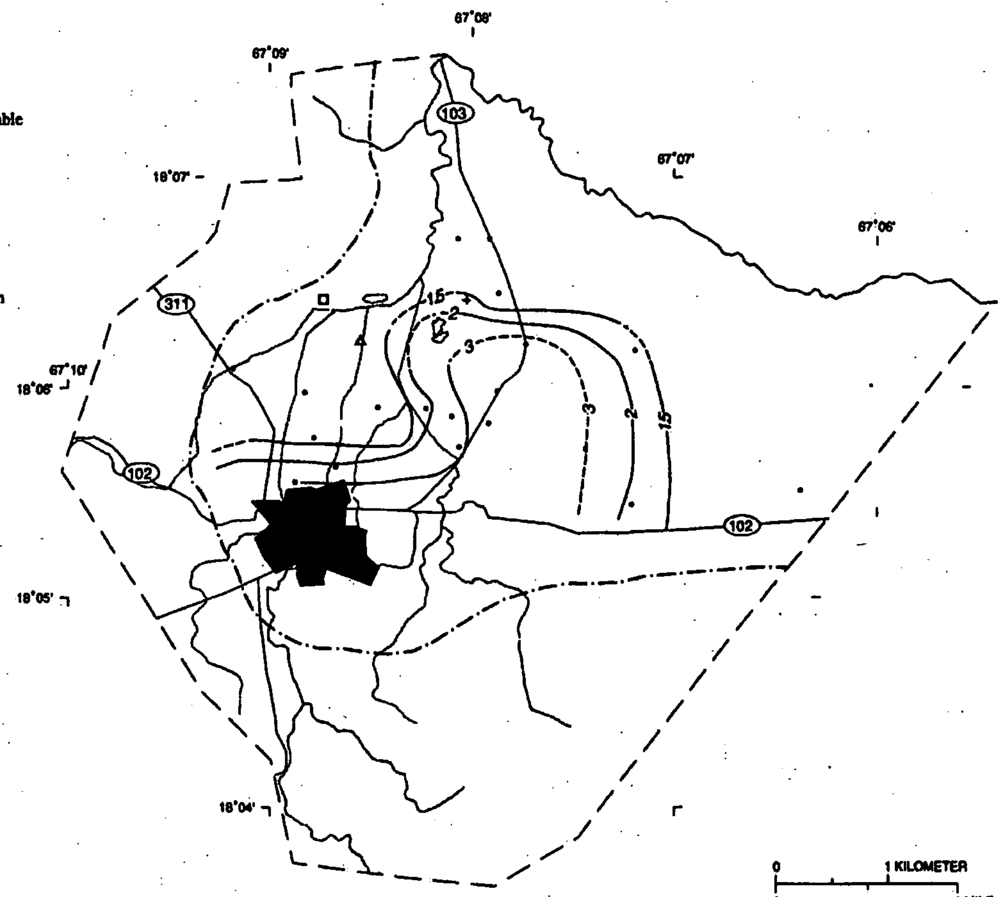
Where:

A_3 = Area within contour of 3 feet of elevation

A_2 = Area within contour of 2 feet of elevation

V_3 = Dewatered volume within contour of 3 feet of elevation

V_2 = Dewatered volume within contour of 2 feet of elevation



Base from U.S. Geological Survey
Puerto Real, Puerto Rico
1:20,000 scale

Figure 11. Water-level decline from June 25 to July 23 and an estimation of the coefficient of storage of that part of the aquifer within the cone of depression in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

Table 4. Chemical analyses of water from selected wells in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico

[Concentrations are given in milligrams per liter unless otherwise noted. Location of wells or piezometers is shown in figure 2. Description of wells is given in table 1. lab, laboratory value; µS/cm, microsiemen per centimeter at 25 degrees Celsius; --, data not available]

Well or piezometer No.	Date	Specific conductance (lab) (µS/cm)	pH (lab) (standard units)	Hardness, total (as $CaCO_3$)	Alkalinity (lab) (as HCO_3)	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Potassium, dissolved	Sodium plus potassium, dissolved
12C	7-09-92	608	8.2	97	263	14	15	46	8.8	55
19A	3-08-93	1,030	7.4	370	467	37	67	90	.6	91
22	7-08-92	752	7.3	360	341	71	44	21	.8	22
30	3-08-93	733	7.7	370	377	53	57	16	.7	16
	7-06-92	736	7.5	380	376	54	59	14	.7	15

Well or piezometer No.	Date	Sulfate, dissolved	Chloride, dissolved	Fluoride, dissolved	Silica, dissolved	Solids, dissolved	Nitrogen, nitrite plus nitrate, dissolved (as N)	Nitrogen, ammonia plus organic, total (as N)	Phosphorus, total (as P)
12C	7-09-92	38	21	0.2	24	325	0.05	2.7	0.12
19A	3-08-93	120	15	.1	41	651	--	.2	.01
22	7-08-92	35	25	.1	51	453	.49	.2	--
30	3-08-93	30	14	.1	52	448	.05	--	.04
	7-06-92	30	18	.2	53	454	--	.2	.04

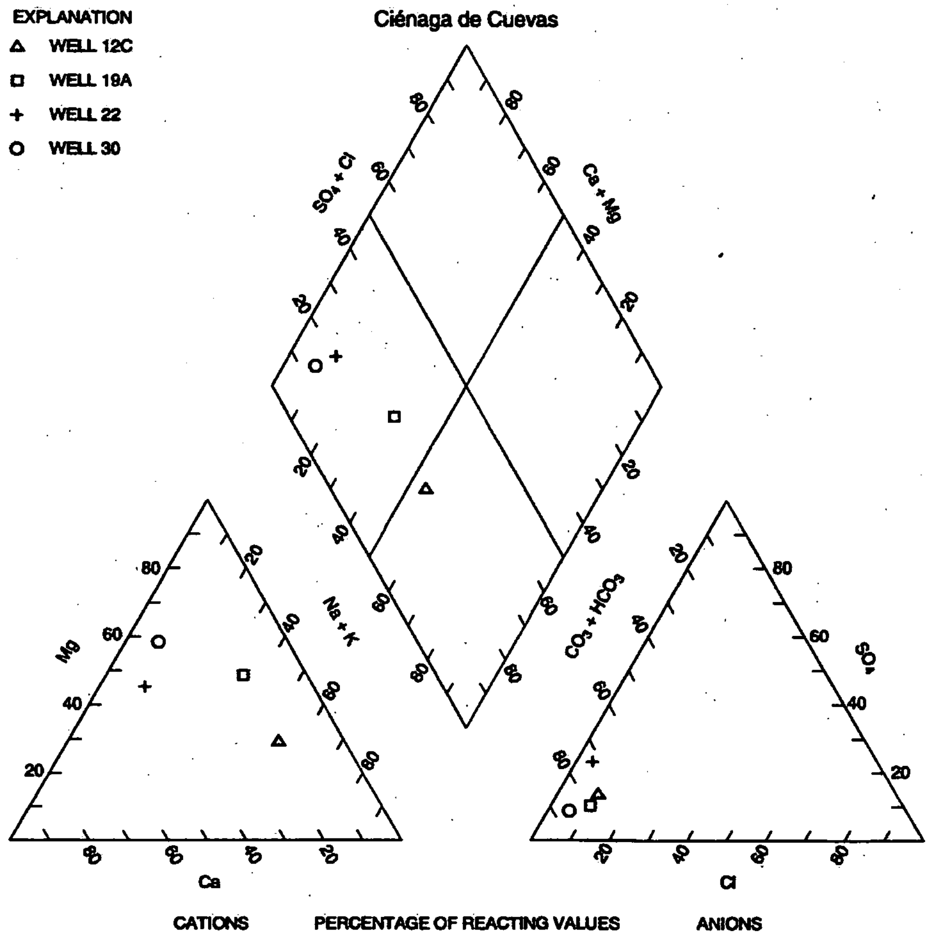


Figure 12. Major constituents in ground water from wells in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

SURFACE-WATER HYDROLOGY

The flatness and semi-enclosed nature of the Ciénaga favors the convergence and accumulation of both the overbank flow of the streams and overland runoff from the surrounding highlands. According to long-time residents in the Bajura area and observations made during the study period, the wetland ponds at least twice a year as a consequence of the two wet seasons that normally occur during April and May and from August through November. The ponding is normally longer and more areally extensive during August through November than during April through May. Pondings occurred in the Ciénaga twice during 1993.

A water level stage-gage station with a continuous recorder was installed at the Ciénaga from January to December 1993 to better understand the intermittent nature of the wetland (fig. 3). However, because of below average precipitation from August through November, the two pondings during 1993 were of significantly less areal extent than similar pondings in the previous year. Runoff during 1993 was not perennial and when streamflow occurred it was only sufficient to maintain the flow in the streams that drain the Ciénaga and to temporarily flood small areas in the wetland. Due to the local and ephemeral nature of the pondings that occurred in the Ciénaga during the two relatively wet periods during 1993, the increases in the water-surface altitude were not sufficiently large to be registered by the stage-gage station during most of the year. The surface-water altitudes, whenever there were small pondings in the Ciénaga (less than 5 acres in extent), were measured instead by an automatic data recorder. These ranged from less than 1 ft from April through June to 2.5 ft from August through November. According to landowners and from visual inspections, as well as manual measurements made in 1992 during the initial field reconnaissance phase of this investigation, the surface-water altitudes in the Ciénaga during that year were as high as 3 and 5 ft above land surface during the April through May and August through September pondings, respectively. There have been occasions in the past where ponding in the wetland has reached altitudes about 10 ft above land surface during large floods such as those that occurred during July 1963 and September 1976 (Hurricane Eloise). The high-water marks of these floods were registered and preserved by a local landowner in the front of his house located near Highway 103 in Barrio Bajura of the municipio of Cabo Rojo (fig. 13). During both of these events, the water in the Ciénaga coalesced with the overbank flooding of the Río Guanajibo and the resulting area under water exceeded 20 mi² (Haire, 1972). Minor pondings occasionally occur as a result of out-of-season rains but, because of their unpredictable nature and short duration, these minor pondings have not been recorded. During periods with little or no rainfall, the wetland shrinks to a series of small isolated pools of water. During extreme drought conditions, even these pools of water cease to exist, according to local landowners.

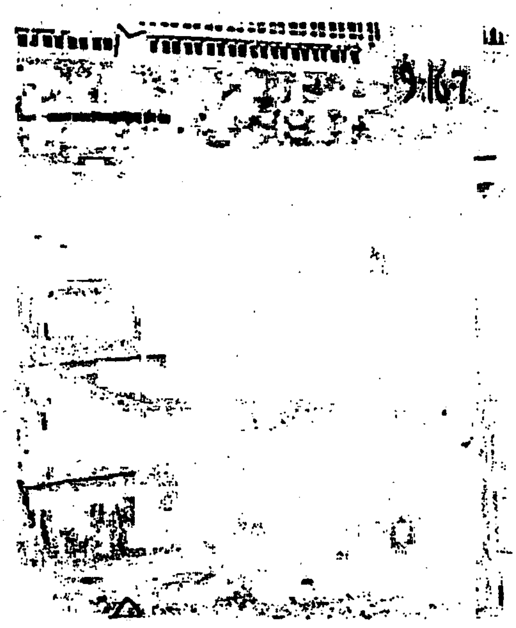


Figure 13. Maximum elevation of the water in Barrio Bajura during Hurricane Eloise as registered by a landowner in front of his house, municipio of Cabo Rojo, southwestern Puerto Rico. (Photo by Rafael Dacosta, U.S. Geological Survey, March 11, 1993.)

Water Quality

Water samples were collected from five sites to determine the concentrations of major dissolved constituents and nutrients in the surface water in the Bajura area (table 5). These chemical data indicate that surface water in the study area is predominantly of the calcium magnesium bicarbonate type and is suitable for most industrial, domestic, and agricultural uses. However, the sanitary quality of the surface water in the study area should be assessed because there is visual evidence that sewage is discharged into some of the local streams.

The differences in residence time of surface water in the Ciénaga appears to be the most important factor influencing the chemical character of this wetland. Because of these differences in residence time, evaporation appears to be an important factor in modifying and differentiating the chemical character of the water between different subareas of the Ciénaga. The chemical character of the water just after it ponds in the Ciénaga results from the mixture in varying degrees of direct precipitation over the wetland, streamflow, and overland runoff from the surrounding highlands. It can be reasonably assumed that differences in the chemical character of the water are minimal just after a significant ponding occurs. The modification and differentiation in the chemical character of the water by evaporation between different parts of the wetland begins after the input of water to the Ciénaga from the various sources ceases or becomes insignificant. The results of chemical analyses on water samples collected in the McDougall and Carlo Ponds define the effects of evaporation in the chemical composition of the water at different subareas in the Ciénaga as a result of variations in the residence time. McDougall Pond is connected to a nearby drainage canal that only flows during and just after rainfall events (fig. 3). A short time after the rainfall ceases, this pond becomes isolated and, with no replenishment from outside sources, the chemical character of the water becomes increasingly affected by evaporation.

Table 5. Chemical analyses of surface-water samples from selected sites in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico

[All concentrations are in milligrams per liter, unless otherwise noted. lab, laboratory value; µS/cm, microsiemen per centimeter at 25 degrees Celsius. --, data not available]

Site	Date	Specific conductance (lab) (µS/cm)	pH (lab) (standard units)	Hardness, total (as $CaCO_3$)	Alkalinity (lab) (as HCO_3)	Calcium, dissolved	Magnesium, dissolved	Potassium, dissolved	Sodium plus potassium, dissolved
Río Viejo at Highway 103	7-07-92	615	8.3	290	289	42	46	1.7	21
Río Guanajibo 2	7-07-92	626	8.2	270	257	27	50	2.8	31
Río Guanajibo 1	7-06-92	623	8.2	270	256	27	49	2.7	133
Carlo Pond	3-08-93	167	6.9	59	74	13	6.5	.9	10.9
McDougall Pond	3-09-93	708	8.0	370	361	24	--	1.4	12.4

Site	Date	Sulfate, dissolved	Chloride, dissolved	Fluoride, dissolved	Silica, dissolved	Solids, dissolved	Nitrogen nitrite plus nitrate, dissolved (as N)	Nitrogen, ammonia plus organic, total (as N)	Phosphorus, total (as P)
Río Viejo at Highway 103	7-07-92	28	26	0.1	33	369	0.11	0.2	0.39
Río Guanajibo 2	7-07-92	35	38	.1	36	371	--	--	--
Río Guanajibo 1	7-06-92	36	38	.1	37	371	1.20	0.3	.61
Carlo Pond	3-08-93	2.6	6.9	.1	15	99	.05	1.3	.10
McDougall Pond	3-09-93	34	14	.1	33	409	.05	2.7	--

In contrast, the Carlo Pond is permanently connected to one of the streams that enters into the wetland and even during periods of no rainfall, this pond is well replenished most of the time. Table 5 tabulates differences in various chemical and physical properties that can be attributed to the varying effect of evaporation on the two sites. Higher values for constituents or properties such as dissolved solids, specific conductance, and chloride provide evidence of the more pronounced effects of evaporation in modifying the chemical character of the water in McDougall Pond than in Carlo Pond.

Water samples analyzed for the stable isotope ratio of oxygen-18 and deuterium (^2H) also support the concept that evaporation has a larger effect in the water quality in McDougall Pond than in Carlo Pond. McDougall Pond water is richer in heavy isotopes (^{18}O and ^2H) than Carlo Pond water, as indicated by a smaller negative delta value for the isotopic composition in McDougall Pond water than that in Carlo Pond water (table 6) (Craig and others, 1963). If a similar initial isotopic composition of oxygen and hydrogen in water from the two ponds is assumed, the higher evaporation rate in McDougall Pond results in the selective removal of the lighter isotopes, ^{16}O and ^1H, and the consequent enrichment of the heavier isotopes, ^{18}O and ^2H, in the residual water of the pond (Craig and others, 1963).

GROUND-WATER/SURFACE-WATER RELATIONS

Analysis of the potentiometric surface distribution in conjunction with the seasonal changes in the ground-water level and the vertical hydraulic gradients indicate that the Ciénaga and segments of the Río Viejo and other streams that drain to the Ciénaga are sources of recharge to the aquifer. This condition exists as a result of the pumping action of a cluster of public water-supply wells. The use of the stable isotopes of oxygen and hydrogen partially supports the

Table 6. Delta values of deuterium (^2H) and oxygen-18 at selected sites in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico

[Delta values are expressed in part per mil differences relative to SMOW (Standard Mean Ocean Water)]

Date sampled	Site	Delta deuterium	Delta oxygen-18
June 9, 1992	McDougall Pond	-12.3	-2.65
July 7, 1992	Río Viejo at Highway 103	-5.5	-1.7
July 7, 1992	Río Guanajibo 2	-5.0	-1.65
July 6, 1992	Well 30	-6.0	-1.95
July 6, 1992	Río Guanajibo 1	-5.0	-1.65
July 8, 1992	Carlo Pond	-8.5	-1.35
July 8, 1992	Well 22	-4.5	-1.60
July 9, 1992	McDougall Pond	19.0	3.85
Nov. 1-30, 1992	Rainfall composite at meteorological station	-24.2	-4.14
Dec. 1-31, 1992	Rainfall composite at meteorological station	9.8	-.65
Mar. 3, 1993	Well 30	-7.5	-2.13
Mar. 8, 1993	Well 19A	-.2	-.64
Mar. 8, 1993	Carlo Pond	2.1	-.87
Mar. 9, 1993	McDougall Pond	6.4	.31
June 9, 1993	Well 24	-7.9	-2.26
June 9, 1993	Well 22	-5.9	-1.75
Jan. 1-31, 1993	Rainfall composite at meteorological station	3.3	-1.17
Feb. 1-28, 1993	Rainfall composite at meteorological station	-.7	-1.53
Mar. 1-31, 1993	Rainfall composite at meteorological station	-6.3	-2.00
Apr. 1-30, 1993	Rainfall composite at meteorological station	4.1	-1.13
May 1-31, 1993	Rainfall composite at meteorological station	-32.9	-5.18
June 1-30, 1993	Rainfall composite at meteorological station	-18.6	-3.27
Aug. 1-31, 1993	Rainfall composite at meteorological station	-21.9	-3.59
Oct. 1-31, 1993	Rainfall composite at meteorological station	-.9	-1.68
Nov. 1-30, 1993	Rainfall composite at meteorological station	-7.6	-2.24
Dec. 1-31, 1993	Rainfall composite at meteorological station	-5.9	-2.13

evidence derived from the analysis of piezometric data regarding the recharge role of the wetland and the streams. The lower reach of the Río Viejo serves as a drainage for the aquifer. The potentiometric-surface distribution and streamflow-seepage studies also indicate that interaction of the Río Guanajibo with the aquifer in the study area is minimal. Furthermore, the hydrologic and hydraulic data also indicate that prior to ground-water development of the aquifer beneath the Ciénaga, the Ciénaga was most likely a discharge rather than a recharge feature of the aquifer.

Ciénaga de Cuevas and the Aquifer

Ground-water-level data indicate that the Ciénaga, under the existing pumping conditions, is a source of recharge to the underlying aquifer. Piezometric data indicate the occurrence of predominantly downward vertical hydraulic gradients in the Ciénaga throughout 1993 (fig. 10). Also, throughout most of 1993, segments of the Río Viejo and Quebrada La Piedra, and to a lesser extent Quebrada Pileta and Quebrada Mendoza, contributed recharge to the aquifer in the Bajura area as shown in figure 8. This recharge is induced by the drawdown maintained by withdrawals from public-supply wells located near the Ciénaga.

Additional evidence that supports the occurrence of significant recharge from the Ciénaga and associated streams to the underlying aquifer is indicated by increases in water levels occurring from April 29 through June 30 and from July 23 through September 29, 1993 (figs. 14 and 15). The higher water level increases range from 4 to 9 ft and occur in the area where the public-supply pumping wells are located. This condition further indicates the existence of a significant infiltration from the streams mentioned above. At a greater distance from the pumping wells and the Ciénaga (about 4,600 ft), the rise in water level was about 2 ft and can be considered to be the result of areal recharge due to rainfall infiltration.

The ground-water levels occurring within that part of the aquifer above the 40-foot contour (fig. 8) represent the ground-water-flow pattern outside the immediate influence of the cone of depression. Ground-water-level fluctuations in the Bajura study area outside the cone of depression were minimal during most of 1993. This indicates that during most of 1993 the source of most of the water withdrawn by public water supply was fairly close to the pumping center and that only a minor fraction of this water was supplied by way of radial flow from outside the cone of depression.

A total recharge of about 777 Mgal (1,400 acre-ft) was estimated to have occurred during the two wet seasons for that part of the aquifer that lies within the cone of depression. This estimate was obtained by calculating the increases in aquifer storage for the time intervals from April 29 through June 25 and from July 23 through September 29, 1993 (these time intervals represent the minimum and maximum potentiometric surface conditions during 1993, as shown in fig. 8) and adding the pumpage by the PRASA wells inside the cone of depression during these two time intervals. These calculations of the increases in aquifer storage are similar to those of the decreases in aquifer storage explained above and used in the estimate of the approximate storage coefficient of the aquifer. These calculations are shown in figures 14 and 15.

The estimated aquifer recharge of about 777 Mgal of water from the Ciénaga during the two annual wet seasons supplied at least 85 percent of the 912 Mgal (or about 2.5 Mgal/d) withdrawn by the PRASA wells during 1993 in the study area. The total annual recharge from the Ciénaga is actually higher than 777 Mgal, because some streams such as Río Viejo sustained flow most of the year. In addition, isolated rainfall events can produce runoff in the streams even if pondings do not occur in the Ciénaga or are ephemeral.

The potentiometric-surface maps in figure 8 depict the predominance of a ground-water divide in the area between the lower reaches of Quebrada Pileta and Quebrada Mendoza. The ground-water divide between these streams indicates that ground water discharges to them. The lower reach of the Río Viejo acts as a drainage feature of the contiguous lower Río Guanajibo alluvial aquifer. The analysis of the data collected during this study indicates that the Ciénaga was most likely a discharge feature of the aquifer prior to development of the PRASA well field. Development of the aquifer has resulted in capture of ground-water flow which previously discharged to streams and has induced infiltration from the Ciénaga. However, construction of a ground-water-flow model would be necessary to evaluate in more detail the hydrologic relation of the Ciénaga and associated streams prior to ground-water development and the effect on the aquifer system resulting from surficial hydrologic modification and ground-water withdrawals.

EXPLANATION

URBAN AREA OF CABO ROJO

— 6 - - LINE OF EQUAL WATER-LEVEL RISE--Interval is 1 foot

—·—· CONTACT OF ALLUVIUM WITH VOLCANIC, METAMORPHIC, AND OLDER SEDIMENTARY ROCKS

— — BOUNDARY OF STUDY AREA

• WELL OR PIEZOMETER

CLUSTER SITE--Site at which one or more observation wells are installed at different depths.

○ Well 11

△ Well 16

□ Well 19A

ESTIMATION OF RECHARGE

$A_2 = 10{,}328{,}064 \text{ feet}^2 \quad V_2 = A_2 \times 2.5 \text{ feet} = 28.8 \times 10^6 \text{ feet}^3$

$A_3 = 8{,}929{,}472 \text{ feet}^2 \quad V_3 = A_3 \times 3.5 \text{ feet} = 31.2 \times 10^6 \text{ feet}^3$

$A_4 = 8{,}843{,}405 \text{ feet}^2 \quad V_4 = A_4 \times 4.5 \text{ feet} = 39.8 \times 10^6 \text{ feet}^3$

$A_5 = 3{,}819{,}232 \text{ feet}^2 \quad V_5 = A_5 \times 5.5 \text{ feet} = 21.06 \times 10^6 \text{ feet}^3$

$A_6 = 2{,}044{,}096 \text{ feet}^2 \quad V_6 = A_6 \times 6.5 \text{ feet} = 13.3 \times 10^6 \text{ feet}^3$

$A_7 = 1{,}452{,}384 \text{ feet}^2 \quad V_7 = A_7 \times 7.5 \text{ feet} = 10.9 \times 10^6 \text{ feet}^3$

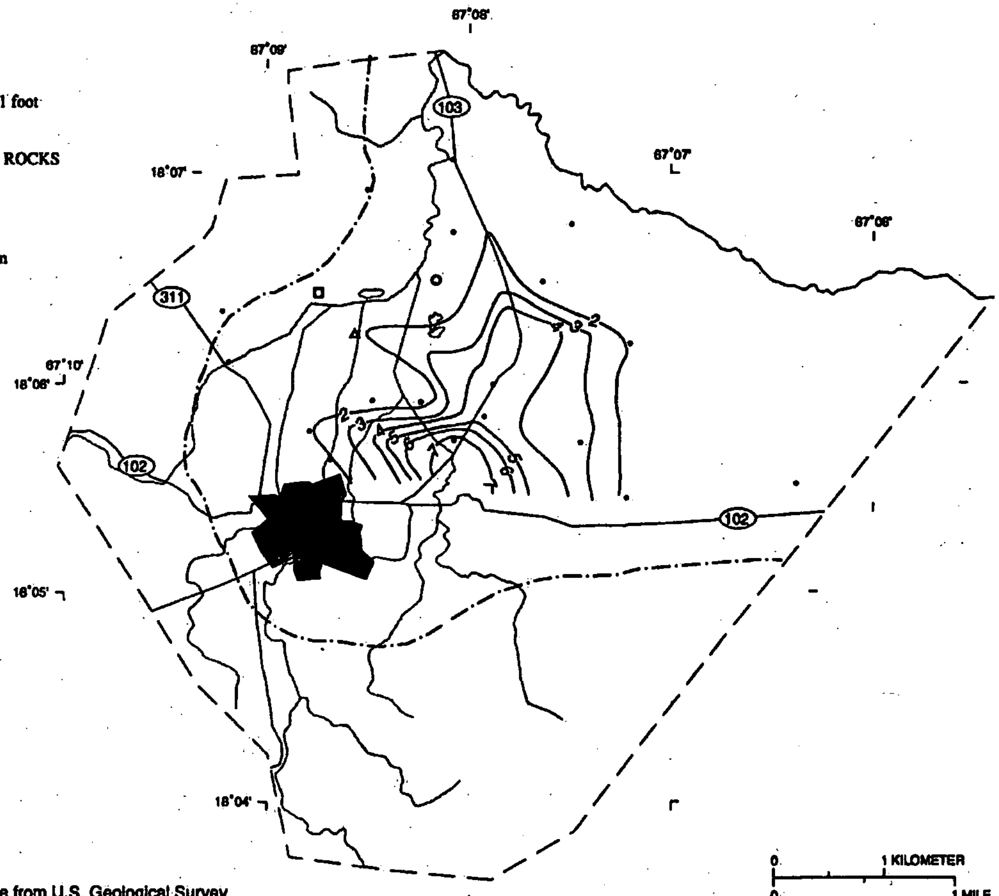
Total volume increase $= V_2 + V_3 + ... + V_7 = 142 \times 10^6 \text{ feet}^3$

Total Recharge = Q pumpage + volume increase (specific yield, April 28–June 30) $= 26 \times 10^6 \text{ feet}^3$ ~ 198 million gallons of water

Where:

A_i = Area in feet^2 between contours i and $i+1$ of water level increase where $i = 2,3,...,7$

V_i = Increase in volume in feet^3 between contours i and $i+1$ where $i = 2,3,...,7$



Base from U.S. Geological Survey
Puerto Real, Puerto Rico
1:20,000 scale

Figure 14. Ground-water level rise and estimate of change in storage from April 29 to June 25, 1993, in that part of the aquifer within the cone of depression in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

EXPLANATION

URBAN AREA OF CABO ROJO

—10— LINE OF EQUAL WATER-LEVEL RISE-- Dashed where approximately located. Interval is variable

CONTACT OF ALLUVIUM WITH VOLCANIC, METAMORPHIC, AND OLDER SEDIMENTARY ROCKS

BOUNDARY OF STUDY AREA

• WELL OR PIEZOMETER

CLUSTER SITE--Site at which one or more observation wells are installed at different depths.

- ○ Well 11
- △ Well 16
- □ Well 19A

ESTIMATION OF TOTAL RECHARGE

A_4 = 12,479,744 feet^2 $V_4 = A_4$ x 4.5 feet = 56.2 x 10^6 feet^3

A_5 = 3,550,272 feet^2 $V_5 = A_5$ x 5.5 feet = 19.5 x 10^6 feet^3

A_6 = 6,885,376 feet^2 $V_6 = A_6$ x 6.5 feet = 44.8 x 10^6 feet^3

A_7 = 5,508,300 feet^2 $V_7 = A_7$ x 7.5 feet = 41.3 x 10^6 feet^3

A_8 = 3,335,104 feet^2 $V_8 = A_8$ x 8.5 feet = 28.3 x 10^6 feet^3

A_9 = 2,797,184 feet^2 $V_9 = A_9$ x 9.5 feet = 26.6 x 10^6 feet^3

A_{10} = 3,335,104 feet^2 $V_{10} = A_{10}$ x 10.5 feet = 35.0 x 10^6 feet^3

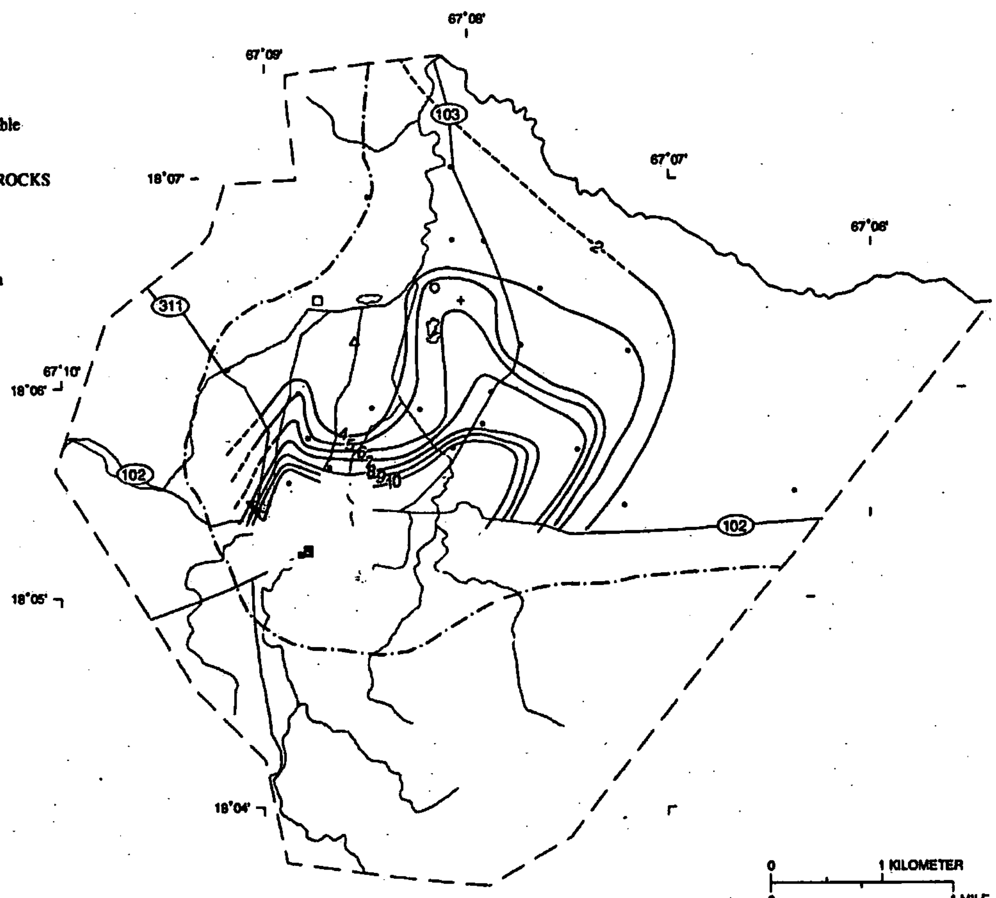
Total volume increase = 252 x 10^6 feet^3

Total Recharge = Q pumpage + volume increase (specific yield, July 28-September 30) = 26 x 10^6 feet^3 - 198 x 10^6 gallons of water

Where:

A_i = Area in feet^2 between contours i and i + 1 of water level increase where i = 2,3,...,7

V_i = Increase in volume in feet^3 between contours i and i + 1 where i = 2,3,...,7



Base from U.S. Geological Survey
Puerto Real, Puerto Rico
1:20,000 scale

Figure 15. Ground-water level rise and estimate of change in storage from July 23 to September 29, 1993, in that part of the aquifer within the cone of depression in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

Río Guanajibo and the Aquifer

The potentiometric-surface maps developed as part of this study, in conjunction with streamflow measurements conducted along the lower reach of the Río Guanajibo, indicate that the interaction of the Río Guanajibo with the aquifer underlying the Ciénaga is minimal or nonexistent. The cone of depression produced by wells 21, 22, and 23 does not extend into the Río Guanajibo (fig. 8). Two seepage runs conducted along a 5-mile stretch of the lower reach of the Río Guanajibo during base-flow conditions in February 1992 and February 1993 confirmed that there was neither gain nor loss in streamflow along the 5-mile stretch at that time. The discharge measurement sites and results of the two seepage runs are shown in figure 3.

Use of Oxygen-18 and Deuterium Isotopes in Defining Recharge Sources

Data on the isotopic composition of oxygen-18 and deuterium were used to complement the hydrologic data in determining the ground-water/surface-water relations in the study area. The isotopic ratios $^{2}H/^{1}H$ (deuterium to protium) and $^{18}O/^{16}O$ (expressed as $\delta\ ^{18}O$ and δ D and expressed as part per mil differences relative to SMOW (Standard Mean Ocean Water) were determined for water samples from surface water (streams and ponds), ground water (wells and piezometers), and for monthly rainfall composites collected at the weather station installed in the Bajura area. The isotopic ratios expressed as $\delta\ ^{18}O$ and δD are presented in table 6 and figure 16. The $\delta\ ^{18}O$ and δD analyses of monthly rainfall composites define what can be considered the local meteoric water line (MWL) for the Bajura area (Craig and others, 1963). Analyses with deviations from the local MWL and plotting on a line with a slope less than 9.5 (slope of local MWL) can be interpreted as water of meteoric origin that has undergone evaporation and becomes relatively enriched in the heavier isotope of oxygen-18 relative to deuterium. The weighted mean for the delta values of oxygen-18 (^{18}O) and deuterium (^{2}H) of the monthly rainfall composites from November 1992 through December 1993 was -2.60 and -10.25, respectively (fig. 16). The weighted mean values of $\delta^{18}O$ and δD could be assumed to be a good approximation of the local mean isotopic signature of the water that recharges the local aquifer, based on the fact that rainfall throughout the study period was near normal (fig. 4). These values could also be considered a reasonable approximation of the corresponding isotopic signatures of the deep ground water in the study area. These values compare favorably with $\delta^{18}O = -2.1$ and $\delta D = -8.23$, calculated for rainfall near Cabo Rojo as functions of mean annual temperatures that used a correlation between $\delta^{18}O$ and δD of surface- and ground-water values. This correlation between $\delta^{18}O$ and δD did not consider evaporation effects (Fernando Gómez-Gómez, U.S. Geological Survey, written commun., 1994).

A representative deep ground-water sample in the study area could not be obtained because either the wells available were not deep enough or fully opened to the aquifer. The $\delta^{18}O$ and δD isotopic analyses of water samples from the Río Guanajibo and the Río Viejo indicate that the isotopic signatures of both streams can be assumed to be similar. Water-quality analyses of samples from the Río Guanajibo and Río Viejo also indicate that streamflow in these streams has been subject to slight evaporation. The evaporation effect is evident in that the $\delta^{18}O$ and δD values of water samples from both streams fall on a line with a slope of 5.7 in the δD versus $\delta^{18}O$ plot for waters in the study area (fig. 16). The $\delta^{18}O$ and δD isotopic signatures of water from wells 30, 22, and 24 lie on the line defined as the MWL for the study area or along the line with a slope of 5.7, indicating evaporation effects are a significant factor (fig. 16). Based on the principle of mass conservation, which also applies when mixing waters of different isotopic signatures, the relative location of plots of the $\delta^{18}O$ and δD signatures of water sampled from these wells could be interpreted as evidence that the water being pumped out of wells in the study area is a mixture of deep ground water, which could be assumed to have an isotopic signature similar to that obtained for the weighted mean rainfall ($S^{18}O = -2.6$; $\delta D = -10.25$) as shown in figure 16, with shallow ground water or surface water showing evaporation effects (plot of $\delta^{18}O$ and δD fall on an evaporation line with a slope of about 5.7 as shown in fig. 16). The water-table surface is usually less than 10 ft below land surface, so it is reasonable to assume that shallow ground water also is affected by evaporation. The isotopic signatures of Carlo and McDougall Ponds, as shown in figure 16, indicate that significant evaporation has affected water samples obtained in

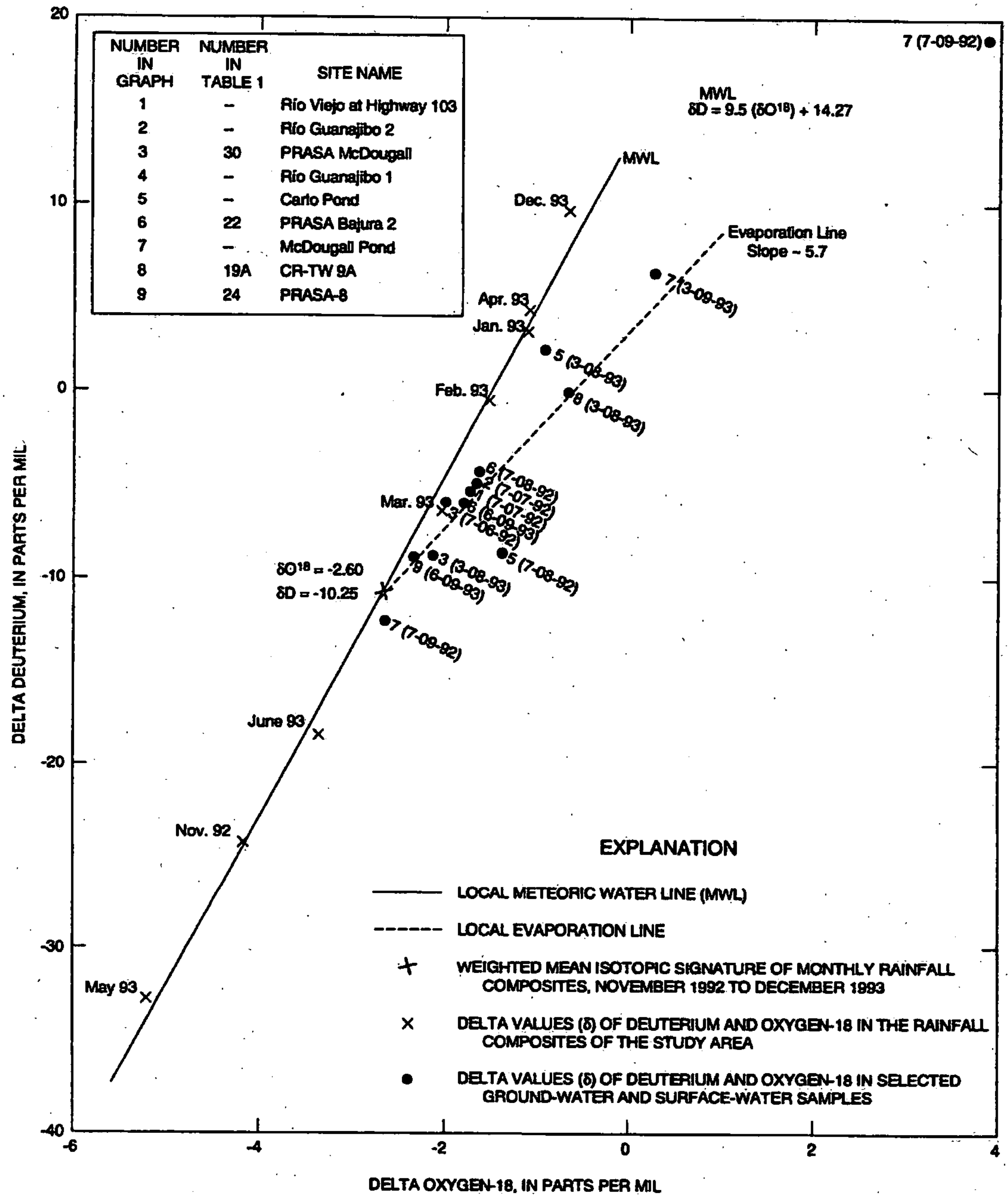


Figure 16. Delta values of deuterium and oxygen-18 in monthly rainfall composites and selected ground-water and surface-water sites in the Bajura area, municipio of Cabo Rojo, southwestern Puerto Rico.

July 1992 at McDougall Pond and in March 1953 at both ponds. The sample from McDougall Pond obtained in July 1982 has the greatest isotopic enrichment, indicating a prolonged period of evaporation.

The isotopic data collected during this study are not sufficient to fully characterize the seasonal and long-term changes in the isotopic signatures of the end members in the hydrologic system defined by the wetland, the underlying aquifer, and the Río Guanajibo. However, these data do provide qualitative indications that an interaction exists between surface and ground water in the study area. Furthermore, these limited and initial isotopic data could be used to design a more comprehensive water-sampling program to quantify more accurately the sources of water to the PRASA well field (deep ground water, shallow ground water affected by evaporation, and local surface-water recharge sources).

SUMMARY AND CONCLUSIONS

The southwestern part of Puerto Rico, particularly the municipio of Cabo Rojo, is undergoing a rapid increase in demand for potable water supply; the result of a sustained population and recreational development. The main source of water in this area is ground water withdrawn from a heterogeneous aquifer in the Bajura area of Cabo Rojo. The PRASA withdraws about 2.5 Mgal/d from this aquifer. It is likely that withdrawals from this aquifer will increase as the demand for water in the area increases and alternative sources are limited to surface-water transfers, which require treatment. A wetland in the Bajura area known as Ciénaga de Cuevas overlies this aquifer. Prior to this investigation the hydraulic relation between this wetland and its associated streams with the underlying aquifer was unknown. In order to define the hydrological interaction and potential ecological value of the wetland and the streams, as well as to ensure the maximum development of the underlying aquifer, the USGS, in cooperation with the PRASA initiated a study to define the hydrogeology and the ground-water/surface-water relations in the Bajura area.

The primary source of ground water is the water-table aquifer, a heterogeneous aquifer composed mostly of limestone and secondary amounts of gravels, sands, and clayey sands. The maximum aquifer thickness is unknown but serpentinite, believed to be the bottom of the aquifer, is present at depths ranging from 125 to 250 ft below land surface. The direction of ground-water movement remained constant through the seasonal changes in 1993. Ground-water flow is dominated by a cone of depression toward wells 21, 22, and 23, which form the principal water-supply well field in the Bajuras area. Outside of the influence of this cone of depression, ground-water flow is toward the lower reach of the Río Viejo, Quebrada Mendoza, and Quebrada Pileta. Seepage-survey data indicate there is no hydraulic connection between the Bajura area water-table aquifer and the Río Guanajibo. The altitude of the water-table surface changed seasonally and areally during the course of this investigation.

Well-performance data obtained from the PRASA files and slug tests conducted in piezometers indicate that the specific capacities in the study area range from 2 to 18 (gal/min)/ft. Transmissivities range from 270 to 5,600 ft^2/d. The horizontal hydraulic conductivities range from 10 to 200 ft/d. Water-level data indicate the existence of vertical hydraulic gradients in the Bajura area. A coefficient of storage of 0.07 was estimated for the aquifer in the Bajura area.

The water associated with the limestone facies is a calcium bicarbonate type; water associated with the shallower terrigenous facies is mostly a sodium bicarbonate type. Ground water in the study area meets the U.S. Environmental Protection Agency's secondary drinking-water standards and is acceptable for most industrial, domestic, and agricultural uses.

Ciénaga de Cuevas is classified as a riverine intermittent wetland. Usually two annual pondings of significance occur in the Ciénaga as a consequence of the two wet seasons that normally occur during April and May and from August through November. The ponding that occurs from August through November is much longer and areally more extensive than the ponding that occurs during April and May. The pondings result from the overbank flow of the streams and drainage canals that cross Ciénaga de Cuevas, surface runoff from the surrounding highlands, and direct precipitation. The chemical character of the water in the wetland appears to be significantly influenced by evaporation, which, in turn, is influenced by the residence time of the water in the wetland. Therefore, differences in water quality between different subareas of the wetland could be explained by the varying effects of evaporation. The chemical data indicate that surface water in the study area is suitable for most industrial, domestic, and agricultural uses. However, the sanitary quality of this water should be assessed because there is visual evidence that sewage is discharged into some of the streams of the study area.

The analysis of the data obtained during the investigation indicated that Ciénaga and associated streams serve as sources of recharge to the underlying aquifer as a result of significant vertical infiltration induced by public-supply wells. The recharge contribution of these surface water to the underlying aquifer was estimated to be about 85 percent of the water withdrawn for public supply during 1993. This estimate only considers the pondings of April through May and August through November and is based on an estimate of the storage coefficient of the aquifer of 0.07. This recharge estimate does not consider recharge from isolated rainfall events that could sustain the streamflow into the wetland and flood small subareas in the wetland. These out-of-season streamflows will tend to increase the vertical recharge to the underlying aquifer. The potential appears to exist for increasing the amount of water withdrawn from the aquifer by inducing more recharge from the overlying wetland and by intercepting a fraction of the water that at present drains into the Río Viejo and segments of other streams by installing properly placed wells.

During the pre-pumping period, the Ciénaga appears to have been a discharge instead of a recharge feature of the underlying aquifer. Apparently, ground water was not only discharged in the lower reach of the Río Viejo but also in the rest of the Río Viejo, and the streams and drainage canals that cross the Ciénaga.

However, the characterization of the hydraulic relation between this wetland and the underlying aquifer is not complete. More information is needed in terms of the vertical and areal distribution of the lithologic and hydrologic characteristics of the underlying aquifer. Similarly, available data are not sufficient to determine if the lack of seepage between the Río Guanajibo and the underlying aquifer is caused by an impermeable barrier or is due to the present pumping pattern.

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